88-05396/

Ministry
of
Transportation
Ontario

REPORT EM-86

FLY ASH IN CONCRETE LABORATORY & FIELD TRIALS IN ONTARIO

Engineering
Materials
Office

EM-86

FLY ASH IN CONCRETE - LABORATORY AND FIELD TRIALS IN ONTARIO

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Engineering Materials Office
Concrete Section
June 1988

ISBN 0-7729-4223-4

SUMMARY

Two type C fly ashes have been evaluated for approval for use as a partial replacement of Portland cement in structural and pavement concrete.

The report describes the field and laboratory tests on concrete made with these fly ashes and recommends that the materials be approved at a maximum cement replacement rate of 10%. The fly ashes should not be used with aggregates from rock formations which are known to have a potential for alkali-carbonate reactivity.

RÉSUMÉ

Deux cendres volantes de type C ont été évaluées afin d'accepter leur utilisation comme remplacement partiel au ciment portland dans la fabrication du béton de structure et de pavage.

La publication décrit les essais en laboratoire et en chantier effectués sur du béton fabriqué avec ces cendres volantes et recommande qu'elles soient acceptées à un taux maximum de remplacement de 10%. Ces cendres volantes ne devraient pas être utilisées avec de gros granulats provenant de formations rocheuses reconnues pour leur possibilité de réaction alcali-carbonate.

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INTRODUCTION

Fly ashes are divided by ASTM[1] and CSA[2] into two classes, Type F and Type C. The first is normally produced by burning anthracite or bituminous coal while the second is normally produced by burning lignite or subbituminous coal. Both of these fly ashes have pozzolanic properties and, in addition, Type C flyash has some cementitious properties[3]. Both types have been used in concrete mixtures by some U.S. state highway departments and have performed satisfactorily[4].

Fly ashes have been used in concrete mixtures in Ontario for many years. However, this use has generally been limited to non-air entrained concrete. There has been reluctance to use Type F fly ashes in air entrained concrete because of a high carbon content and/or an excessive variation in carbon content causing difficulties in the control of air content.

Carbon content is usually assumed to be approximately equal to the loss on ignition. Type C fly ashes vary in the loss on ignition values which may be as high as 10% or more. However, the values are usually less than 1.0%[3] and these values do not normally cause problems in the air entraining of concrete mixtures.

The chemical and mineral composition of fly ashes, as well as their physical properties and chemical activity in Portland cement concrete, is summerized in the ACI Committee 226 report[3]. Since the composition, physical properties and effects on the properties of fresh and hardened concrete depend to a large degree on the source of fly ash, it is necessary to evaluate fly ash from each source proposed for use.

Great Lakes Fly Ash has been marketing Type C fly ash since 1984 from two sources. One of them is the Detroit Edison plants in St. Clair, Michigan and the other Ontario Hydro Generating Station in Thunder Bay and Atikoken, Ontario. The Ministry has been requested by Great Lakes Fly Ash to allow the use of these Type C fly ashes in concrete for its projects. It was stated that the fly ashes would not have detrimental effects on the properties of concrete and that the main benefit would be a significant reduction in cost of the concrete. The request instigated an evaluation of the fly ashes. The evaluation was carried out during the period of April 1986 to June 1988.

OBJECTIVES

The evaluation was designed to determine:

i) compliance of each of the two Type C fly ashes with the requirements of CSA Standard CAN3-A23.5-M86[2].

ii) the effect of each fly ash on the strength, volume change, freeze-thaw durability, salt scaling and chloride permeability of laboratory concrete using 2 cement brands, 2 classes of concrete and fly ash replacements of 0, 10, 25 and 40% as variables.

and iii) field performance of 30 MPa class concrete containing 25% fly ash, by mass of total cementing materials, in a structure barrier wall.

with a view to approving the use of the fly ashes in Ministry structural concrete.

FLY ASHES TESTED, COMPLIANCE WITH CSA STANDARDS

The requirements of CSA Standard CAN3-A23.5-M86 for Type C fly ash are the same as those of ASTM C 618-85 with the latter having also a chemical requirement for $SiO_2+AL_2O_3+Fe_2O_3$ content and a physical requirement for water demand. Each of the two fly ashes was tested for the properties specified by the CSA Standards. The physical test results are shown in Table A, and chemical in Table B. Both, the St. Clair and Thunder Bay fly ashes complied with the requirements of the CSA Standard. They also complied with the ASTM requirment for a minimum $SiO_2+AL_2O_3+Fe_2O_3$ content of 50% and for water demand of max. 105% (the highest was 92%).

LABORATORY TESTS

Cements, aggregates, water and admixtures used in all laboratory tests are described below:

Cements

The cements used in the laboratory test were Type 10 from Lafarge Canada Inc. plant in Woodstock (Cement A) and St. Lawrence Cement Co. plant in Mississauga (Cement B). Their physical and chemical properties are shown in Table A and B, respectively.

Aggregates

The fine aggregate was a good quality natural sand from Consolidated Sand and Gravel, Guelph having a fineness modulus of 2.68, absorption 0.79%, and bulk relative density 2.697. The coarse aggregate was a good quality dolomitic limestone from Nelson Quarry having a bulk relative density of 2.650, and absorption 1.48%. The coarse aggregate was sieved into a number of sizes and then recombined to produce the following gradations:

Sieve Size	% Retained
19 mm	0
13.2 mm	33
9.5 mm	66
4.75 mm	100

The aggregates complied with the requirements of OPSS 1002[5].

Admixtures

The water reducing strength increasing admixture was PDA 25XL. The admixture complied with the requirements of CSA Standard CAN3-A266.2-M78[6]. It is of a calcium lignosulphonate type, it had a non-volatile content of 45.0% and relative density 1.221. It was added to each mix at a dosage of 285 mL per 100 kg of total cementing material. The air-entraining admixture was Pro-Air. It is a mixture of the saponified wood resin and sulphonated hydrocarbon types complying with the requirements of CSA Standard CAN3-A266.1-M78[7]. Both admixtures are manufactured by Conchem, Milton.

Test Program

Each of the two fly ashes was tested at a replacement rate of 0, 10, 25 and 40% by mass of total cementing material in concrete mixes of 20 MPa and 30 MPa classes made with each of the two cement brands. A total of 28 mixes were designed and two 50 L batches of concrete were made with each of the mix designs. Each batch of the same design had the same water-cement ratio with the exception of an inadvertant difference for mix L797/86 (Table E). Each batch had a slump of 80 ± 10 mm and air content of 6 ± 1%. The tests carried out, the number and size of specimens as well as which batch provided concrete for the specimens are shown in Table C.

Mixing Concrete, Fabrication and Curing Of Test Specimens

The concrete batches were mixed and test specimens fabricated in accordance with CSA Test Method A23.2-2C[9]. The fresh concrete tests were carried out in accordance with the appropriate method of CSA Standard CAN3-A23.2-M77[8]. The test specimens were cured as described in Table C.

Test Procedures

The test procedure for each of the tests carried out is shown in Table C. The salt scaling test was as described in ASTM C 672-84 with the exceptions that the deicer was a 3% sodium chloride solution and that the resistance to scaling was expressed as a dry mass of flaked off material per m^2 of the area exposed to scaling. The mass loss was determined and the solution was replaced after each 5 cycles.

Test Results

The test results obtained on the fresh concretes and the strength test results are shown in Table D to G while the freeze-thaw, salt scaling, shrinkage and rapid chloride permeability test results are in Table H to K. Compressive strength and splitting tensile strength results are also shown in Figure 1 to 8, and salt scaling results in Figure 9-1 to 12-4.

Compressive Strength (Table D to G, Figure 1 to 4). There is a significant difference in the performance of St. Clair fly ash with cement A and cement B. The strength of the mixes in the cement A was generally dependent on the fly ash content and it increased with an increase in the fly ash content. The mixes with the 40% fly ash content by mass of total cementing material developed compressive strength at least 20, 28, 23 and 12% higher at 3, 7, 28 and 91 d, respectively, than the control mix. The strength of the mixes with the same fly ash and cement B did not vary as much as the mixes with cement A. In this case the strength of the 20 MPa control mix was generally higher at all ages than the strength of any of the 20 MPa mixes with the fly ash and there was generally a decrease in the strength with an increase in the fly ash content. The strengths of the 35 MPa mixes were much closer than the strengths of the 20 MPa mixes and it is difficult to distinguish a trend as the differences may be due to the precision of the test.

The strength of the Thunder Bay fly ash mixes was generally lower at 1 and 3 d and generally higher at later ages than that of the control concrete. At the later ages, the strength generally increased with an increase in the fly ash

content. The 28 d and 91 d strengths were of approximately the same magnitude as those of the mixes with the St. Clair fly ash.

Splitting Tensile Strength (Table D to G, Figure 5 to 8). The splitting tensile strength test results show similar trends to those described above for compressive strengths.

Rapid Chloride Permeability (Table H to K). There is a very consistent trend in the chloride permeability test results. In all test series, with the exception of one, the mixes without fly ash showed the highest permeability and the permeability decreased with an increase in the fly ash content. The exception was the 35 MPa mix L788 with 10% of St. Clair fly ash and cement B (Table K). This mix had a rapid chloride permeability of 5580 coulombs while the mix without the fly ash had a permeability of 4092 coulombs. It appears that this discrepancy was caused by a somewhat higher water-cement ratio of the fly ash mix as compared to the mix without the fly ash.

Freeze-Thaw Durability (Table H to K). All the mixes had an excellent freeze-thaw durability (durability factor >90%) with the exception of mix L805 (Table H) and mix L788 (Table K) which produced a relatively low but adequate durability factor (80.4 and 79.6, respectively) and a relatively high expansion (+0.118 and +0.091, respectively) after exposure to 300 freeze-thaw cycles. Although the air void system determined on a vertical section of one of the two scaling slabs for each mix is acceptable in both of these cases, there is still possibility that the air void system in the freeze-thaw prisms was inadequate for the exposure. The prisms were in advertantly discarded before they could be examined.

Salt Scaling (Table H to K, Figure 9-1 to 12-4). As expected, each of the two classes of concrete, made with either of the two cement sources and containing either of the two fly ashes, generally, scaled more than the concretes without the fly ashes. There were only two cases (Figure 10-1, Thunder Bay fly ash and Figure 11-1, St. Clair fly ash) where the concrete without fly ash had a slightly higher mass loss at 50 cycles than the concrete with the lowest amount (10%) of fly ash.

Generally, the amount of scaling increased with an increase in the fly ash content. The exceptions were the two 35 MPa mixes made with cement B (Figure 12-1). In these two cases the concretes with a 25% fly ash content scaled more than those with a 40% fly ash content. Although the precision of the salt scaling test is relatively poor, these rather large differences cannot be attributed solely to the precision of the test.

Extra salt scaling slabs were used for the determination of the air void system of several slabs to see whether the scaling resistance was related to the air void system of the concrete. The air void system results are shown in Table H to K. There was no indication that the increased scaling of fly ash mixes was caused by an inferior air void system in these mixes.

Change in Length (Drying Shrinkage) (Table H to K). It is evident from the data that in all cases, with the exception of two, the drying shrinkage of the fly ash mixes is not higher than that of the corresponding mix without fly ash. The exceptions are mix L787/86 (Table J) and mix L707/87 (Table K). The first mix

had a change in length of -0.024% at 28 d while the shrinkage of the corresponding mix without fly ash (L763/86) was -0.022%. Since the change in length of this mix at 7 d and 90 d was smaller than that of the mix without fly ash, it appears that the difference at 28 d was due to a testing error. The second mix produced higher shrinkage only at 3 d so it was probably also a testing error.

FIELD TESTS

Only the St. Clair fly ash was tested in the field. Table A shows the physical properties and Table B the chemical properties of the field batch of the fly ash. It was used in combination with Type 10 cement from Canada Cement Lafarge's plant in Bath. The mix was a typical 30 MPa mix with a type WN admixture and an air entraining admixture. The only difference between the control mix and the test mix was that in the latter 25% of the cement by mass was replaced with the fly ash. Table L shows the details of the mixes and the test results on the fresh as well as on the hardened concrete.

The tests were carried out on Contract 85-35. They involved a barrier wall on the Hwy. 8 to Hwy. 401 east bound ramp structure. The wall was erected using steel forms and the conventional forming method. The whole length (approx. 150 m) from the west to the east expansion joint was divided into 24 panels. The panels were identified as #1 at the west expansion joint to #24 at the east expansion joint. The concrete was placed first in the even number panels and, generally, the next day in the adjacent odd number panels (Figure 14). The fly ash concrete was placed in each of the even number panels from #2 to #20. The wall was erected in late May-early June 1986.

The inner surface of the wall has a south-west exposure.

Laboratory Tests on Field Concrete

Two loads of the concrete without fly ash and two loads of the concrete with the fly ash were sampled on different days for slump, air content, compressive strength, freeze-thaw resistance, salt scaling resistance and air void system tests (Figure 13). The test results are shown in Table L to N and Figure 15 and Figure 16-1 to 16-5.

Fresh Concrete (Table L). The slump of the control and fly ash concretes was maintained within 60-100 mm and the air content within 7.0± 1½%. Each of the two test loads of the fly ash concrete had a higher air content and higher temperature than either of the two control test loads but they were within the limits. No obvious differences were observed between the cohesiveness and mobility of the two types of the concrete other than the fly ash concrete being a little lighter in colour. The water content of the test mix and the control mix was reported to be the same but it was a maximum water content, not the actual. The actual water content of the test mix was probably lower than that of the control mix.

Compressive Strength (Table L, Figure 15). The strength of the test concrete was significantly lower than that of the control concrete. This was contrary to our findings in the laboratory program. Since the test loads had a higher air content and higher temperatures than the control loads, some of the difference can be attributed to these two factors. Because of these difference in the strength, Lafarge Canada Inc. arranged for 100 mm cores from the wall for compressive strength tests and for the testing of the wall by the impact

hammer. The impact hammer tests on 5 fly ash and 5 control concrete panels in August 1986 produced an average strength of 27.3 MPa and 27.8 MPa, respectively. The cores were obtained on October 16, 1986 and tested on October 22, 1986, about 140 days after placing. Six cores were cut from the control concrete (3 cores per panel) and six from the fly ash concrete (3 cores per panel). One of the fly ash concrete and one of the control concrete panels cored were constructed from the loads of concrete sampled for the casting of the standard concrete cylinders. When the core strength for these panels are compared (Table M), it is evident that the fly ash concrete is lower in strength than the control concrete by approx. 15%. The figure for the cylinders is 28%. For the other panel cored the test mix panel was less than 1% below the control. This confirms that the strength of the fly ash concrete was lower than that of the control concrete but the difference decreased with age. Comparison of the 28 d cylinder strengths to 136-140 d core strengths indicates that the fly ash concretes increased approximately 10 mPa in strength from 28 d to 136-140 d whereas the control concretes increased less than 3 mPa in the same period.

Freeze-Thaw Resistance (Table L). Both the fly ash and the control concretes had an excellent resistance to 300 freeze-thaw cycles with no significant differences between the two concretes.

Salt Scaling Resistance (Table L, Figure 16-1 to 16-5). The performance of the field made slabs was similar to that of the laboratory made slabs in that the fly ash concrete slabs scaled more than the control concrete slabs. The difference between the two types of the concrete is substantial (avg. mass loss of 0.306 vs 1.714 kg/m^2).

Air Void System (Table N). The test was carried out by MTC on extra salt scaling slabs and by Canada Cement Lafarge on cores. It is evident from the table that in all cases tested the concretes had an excellent air void system; i.e. sufficiently high air content (>3.0%), specific surface generally much higher than 25 mm^{-1}, and spacing factor substantially lower than 0.20 mm. The higher scaling of the fly ash than the control concrete can not be attributed to its air void system.

Performance Of The Barrier Wall

The barrier wall was inspected on June 23, 1986, September 24, 1987 and March 3, 1988. The bridge was opened to traffic in the Fall of 1987 so that the wall was well matured before it was exposed to freezing and thawing in the presence of deicing salt.

The first inspection (86 06 23) found that almost every control and fly ash concrete panel developed a vertical crack approximately in the mid length (Figure 17). The cracks were wider at the top of the wall and terminated at approximately mid height. There was an indication that most of the barrier construction joints were working. The fly ash panels had a lighter colour than the control panels and had a yellow tint. A grout consisting of 1 part Portland cement, 1 part of white cement and six parts concrete sand was rubbed into the surface to fill the bug holes (Figure 18).

The second inspection (87 09 24) found that some panels developed a second vertical crack and that the yellow tint (and lighter colour) was still well pronounced in the fly ash panels. It was also noticed that there were areas of crazing in the sloping section of some fly ash as well as some control panels. The bridge was not open to traffic yet.

The third inspection (88 03 03) was after the wall had been exposed to salt splash for almost the entire first winter. No sign of surface scaling was found in either the fly ash or the control panels. However, the fourth inspection revealled some light to moderate scaling at the base of many fly ash and some control panels (Figure 19, 20). The scaling is more severe on the fly ash then the control panels.

EFFECT ON OTHER PROPERTIES

This laboratory and field series of tests covered the strength, freeze-thaw, permeability and drying shrinkage of concrete containing the fly ashes. However, there are other properties - setting time, bleeding, alkali-aggregate reaction, modulus of elasticity, creep, corrosion and sulphate resistance that have not been determined by this project. Some of these properties have been investigated by Lafarge Canada Inc. and reported by N.R. Elmhirst[12]. General information on the remaining properties of Type C fly ash concrete can be obtained from the recent reports of ACI Committee 226[3] and TRB[4].

Great Lakes Fly Ash[12]tested both the St. Clair fly ash and the Thunder Bay fly ash. The bleeding test was carried out on mixes with a relatively low cementing material content (225 kg/m^3-St. Clair fly ash, 275 kg/m^3-Thunder Bay fly ash). It showed that the volume of bleed water decreased substantially with increasing fly ash content. There was a slight decrease in the initial and final setting time with increasing fly ash content. No significant differences were reported between the setting time of 0 and 20-25% fly ash concretes at 10, 23-25 and 33-38°C. It was determined that the addition of the fly ash had a beneficial effect on sulphate resistance and alkali-silica reaction. However, the alkali-carbonate reaction was adversely affected by the addition of the fly ash and the expansion increased with increasing fly ash content.

The ACI report[3] states that "with 20 percent replacement, creep strains are about the same; at above 20 percent, creep increased with increasing fly ash content". There is no statement on the effect of Type C fly ash on the modulus of elasticity. However, since the strength of fly ash concrete is generally not lower and the density is only slightly lower than that of concrete without fly ash, it is unlikely that there is a significant difference in the modulus of elasticity of the two concretes. Since fly ash concrete has a reduced permeability, it should also provide a greater resistance to reinforcing steel corrosion.

GENERAL DISCUSSION

The fly ash has an adverse effect on two concrete properties; alkali-carbonate reactivity and salt scaling. Although the Ministry does not allow the use of alkali reactive aggregates, there is a danger that a replacement of Portland cement with one of the fly ashes in concrete containing an acceptable but borderline carbonate aggregate, will cause cracking. Because of this possibility, these fly ashes should not be used with aggregates from rock formations which are known to have a potential for alkali-carbonate reactivity.

The salt scaling tests point out that concrete with fly ash scales more than concrete without fly ash. This is reported also by other investigators[3,4, 12,13]. The salt scaling resistance of concrete containing ground granulated blast furnace slag is similar to that of the fly ash concrete. In spite of the high loss in the laboratory tests, there is no indication in the field that concrete with up to 25% GGBF slag scales more than 100% Portland cement concrete

or that there are more incidents of scaling of concrete with GGBF slag. The TRB report[4] attributes this difference between the laboratory and field performance to the test conditions being generally more severe than the environmental conditions to which the concrete is exposed. It also states that greater surface scaling has been reported for some experimental installations but when such scaling occurs it does not affect the internal structure and integrity of the concrete. There is some uncertainty about the performance of fly ash concrete in the field and, because of this, the use of concrete with large amounts of fly ash should not be allowed by the Ministry until it is justified by the field performance. It would be prudent to approve the materials at an initial cement replacement rate of 10% and increase this rate gradually if the field performance warrants the increase.

CONCLUSIONS

On the basis of this investigation it is concluded that:

i) The fly ashes from St. Clair and Thunder Bay plants comply with the requirements of OPSS 1301, Material Specification for Hydraulic Cementing Materials for Type C fly ash.

ii) At approx. the same slump, air content and cement content, concrete containg either of the two fly ashes had a lower water-cement ratio than that of the control (100% Portland cement) concrete. The water-cement ratio decreased with increasing fly ash content.

iii) Concrete made with either of the fly ashes had, generally, lower strength at early ages (1 d, 3 d) and, generally, higher strength at later ages (28 d, 90 d) than the corresponding control concrete. This difference was larger and more consistent for the Thunder Bay fly ash than the St. Clair fly ash. There were no significant differences between the 10% fly ash concrete and the control concrete. Generally, the strength at later ages increased with increasing fly ash content. The maximum increase in 28 d strength was approx. 25%. This occured with 40% fly ash content and Cement A. Cement B in combination with either of the two fly ashes produced generally lower strength than Cement A.

iv) The field fly ash concrete produced approx. 20% lower 28 d cylinder compressive strength and approx. 9% lower 136-140 d core strength than the control concrete. However, the impact hammer tests on several panels at 124-128 d showed no significant differences between the fly ash and control concretes.

v) The trend in the relationship of the splitting tensile strength of the fly ash concrete to that of the control concrete was approximately the same as for the compressive strength.

vi) The drying shrinkage of the fly ash concrete was lower in all cases than that of the control concrete. Generally, the shrinkage decreased with increasing fly ash content.

vii) The chloride permeability of the fly ash concrete was lower than that of the control concrete and decreased with increasing fly ash content.

viii) The freeze-thaw durability of the laboratory and field fly ash concrete was excellent.

ix) The salt scaling resistance of the fly ash concrete was lower than that of the control concrete and, generally, scaling increased with increasing fly ash content. The 10% fly ash mixes scaled not more than mixes made with 25% ground granulated blast furnace slag of the same class. The field mixes with 25% St. Clair fly ash scaled approximately as much as the laboratory 10% fly ash mixes. The fieldfly ash as well as control concrete had an excellent air void system, considerably better than the laboratory concrete but there was no indication that the mass loss of the laboratory mixes was dependent on their air void syst.

x) Lafarge Canada Inc. reports that Type C fly ashes reduce expansion due to alkali-silica reaction but increase it in the case of alkali-carbonate reaction.

xi) Many of the structure barrier wall panels containing 25% St. Clair fly ash and some of the control panels have developed light to moderate scaling at the base of the wall. The scaling is more severe on the fly ash than the control panels.

RECOMMENDATIONS

Since large amounts of either of the two Type C fly ashes can have some adverse effect on early strength of the concrete and a considerable adverse effect on the salt scaling resistance, it is recommended that the materials be approved by the Ministry for use in structural and pavement concrete (except lean concrete base) at a maximum cement replacement rate of 10%. The fly ashes aggravate alkali-carbonate expansion, thus, they should not be used with aggregates from rock formations which are known to have a potential for alkali-carbonate reactivity.

Ground granulated blast furnace slag has been used in this Ministry's concrete at a maximum replacement rate of 25% for several years. A laboratory and field performance investigation is now in progress to determine whether a higher maximum cement replacement rate than 25% can be allowed without objectionable effects on the concrete. A cement replacement with a combination of ground granulated blast furnace slag and Type C fly ash is also under study. Until these investigations are completed, the total amount of the supplementary cementing materials should not exceed 25% by mass of the total cementing material.

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TABLE A. PHYSICAL PROPERTIES OF PORTLAND CEMENTS AND FLY ASHES "C" USED IN THE TESTS

IDENTIFICATION	LABORATORY PROJECT				FIELD PROJECT			REQUIREMENTS (CSA)	
	Portland Cement Type 10		Fly Ash Type "C"		Portland Cement Type 10		Fly Ash Type "C"	CAN3-A5-M83 for Portland Cement Type 10	CAN3-A23.5 -M-86 for Fly Ash Type "C"
	85-L-15 Woodstock	85-L-01 Clarkson	86-L-02 Thunder Bay	86-L-05 St. Clair	86-L-11 Bath	86-L-15 Bath	86-L-14 St. Clair		
Fineness									
-pass 45 um sieve, %	93.1	83.4	85.8	88.2	86.8	84.7	90.9	min. 72	min. 66
-Blaine, m2/kg	389	365	285	410	373	418	532	-	-
Soundness, % exp.	0.100	0.174	0.056(.162)*	0.566(.666)*	0.044	0.034	-	max. 1.0	max. 0.8
Time of setting, min	125	105	-	-	110	110	-	45-360	-
False set, %	90	69	-	-	51.4	50	-	min 50	-
Increase of drying shrinkage of mortar bars, 28 days %	-	-	-0.007(-0.008)*	-0.005(-0.024)*	-	-	-	-	max. 0.03
Relative density	-	-	2.44	2.58	-	3.16	2.56	-	-
Accelerated pozzolanic activity index, %	-	-	86.6(111.0)*	94.9(99.6)*	-	-	99.3**	-	min. 68
Pozzolanic activity index, %	-	-	91.6(112.8)*	95.8(96.5)*	-	-	98.9**	-	min. 75
Compressive strength, MPa									
3d	21.4	22.9	-	-	24.4	24.0	-	min. 12.5	-
7d	26.2	27.4	-	-	28.5	26.7	-	min. 18.0	-
28d	35.0	33.1	-	-	36.2	33.6	-	min. 26.5	-

* the figures in parenthesis refer to the blend with portland cement 86-L-01, while the figures without parenthesis refer to the blend with portland cement 85-L-15

** blended with portland cement 86-L-11

TABLE B. CHEMICAL PROPERTIES OF PORTLAND CEMENTS AND FLY ASHES "C" USED IN THE TESTS

IDENTIFICATION	LABORATORY PROJECT				FIELD PROJECT			REQUIREMENTS (CSA)	
	Portland Cement Type 10		Fly Ash Type "C"		Portland Cement Type 10		Fly Ash Type "C"	CAN3-A5-M83 for Portland Cement Type 10	CAN3-A23.5 -M-86 for Fly Ash Type "C"
	85-L-15 Woodstock	85-L-01 Clarkson	86-L-02 Thunder Bay	86-L-05 St. Clair	86-L-11 Bath	86-L-15 Bath	86-L-14 St. Clair		
Loss on ignition, %	1.71	0.54	0.41	0.95	2.86	2.56	0.52	max. 3.0	max. 6.0
Insoluable residue, %	0.13	0.35	1.50	1.00	0.60	0.64	-	max. 1.0	-
Tricalcium aluminate, %	5.36	13.16	-	-	9.66	9.21	-	-	-
Sulphur trioxide, %	2.70	2.75	1.39	4.70	3.35	3.24	4.47	max. 3.5*	max. 5.0
Magnesium oxide, %	3.40	2.50	3.52	3.79	2.17	2.23	-	max. 5.0	-
Sodium oxide, %	0.52	0.22	4.50	5.30	0.27	0.29	-	-	-
Potassium oxide, %	0.53	1.30	0.48	0.61	0.94	1.00	-	-	-
Alkali content, %	0.89	1.08	4.82	5.70	0.89	0.94	-	-	-
Silicon dioxide, %	20.89	20.59	45.16	33.42	20.26	20.32	-	-	-
Aluminum oxide, %	3.82	6.27	22.49	20.47	5.03	5.02	-	-	-
Ferric oxide, %	2.82	2.04	4.31	7.89	2.17	2.42	-	-	-
Calcium oxide, %	63.57	63.89	13.30	18.14	62.95	62.92	-	-	-
Moisture content, %	-	-	not tested	not tested	-	-	0.04	-	max. 3.0
$SiO_2+AL_2O_3+Fe_2O_3$, %	-	-	71.96	61.78	-	-	-	-	-

* maximun 3.0 % if the $C_3A \leq 7.5$ %

TABLE C. LABORATORY TESTS, SIZE AND NUMBER OF SPECIMENS

TEST	SPECIMEN		# OF SPECIMENS MADE FROM BATCH		CURING REGIME	TEST METHOD
	TYPE	SIZE, mm	A	B		
Compressive strength 1,3,7,28,90d	cylinder	100x200	1 for each age	2 for each age	Moisture room	CAN3-A23.2-M77 Method A23.2-9C (see reference 8)
Splitting tensile strength 1,3,7,28,90d	cylinder	100x200	1 for each age	2 for each age	Moisture room	CAN3-A23.2-M77 Method A23.2-13C (see reference 8)
Volume change (shrinkage)	prism	75x75x400	3	-	Moisture room for 28 d followed by storage at 23±2°C and 50±5% R.H.	ASTM C 157-86 (see reference 11)
Freeze-thaw	prism	75x75x400	3	-	Moisture room for 14 d	ASTM C 666-84 Procedure A (see reference 11)
Salt scaling	slab	300x300x75	1	1	Moisture room for 14 d followed by storage for 14 d at normal lab air conditions	ASTM C 672-84 with the exception described under Test Procedures in this report
Rapid chloride permeability	disk*	100x50*	2	-	Moisture room for 28 d	AASHTO designation: T277-83 I (see reference 10)
Air void system	scaling slab after completion of scaling test	300x75	any one of the two slabs		-	ASTM C 457-82a (see reference 11)

* Specimen taken from a 100x200 cylinder.

TABLE D. MIX PROPORTIONS, FRESH CONCRETE AND STRENGTH TEST RESULTS
20 MPa CONCRETE, CEMENT A

MIX NUMBER	Control		St. Clair Fly Ash				Thunder Bay Fly Ash					
	L762/86		L777/86		L791/86		L703/87		L765/86		L789/86		L805/86	
FLY ASH, %, by mass of total cementitious material	0		10		25		40		10		25		40	
Mix Proportions per 50 L batch														
Cement, kg	15.5		14.0		11.6		9.3		14.0		11.6		9.3	
Fly Ash, kg	-		1.5		3.9		6.2		1.5		3.9		6.2	
Coarse Aggregate, kg	53.2		53.2		53.2		53.2		53.2		53.2		53.2	
Fine Aggregate, kg	39.8		39.0		38.6		38.0		38.9		38.3		37.8	
PDA 25XL, mL	44.2		44.2		44.2		44.2		44.2		44.2		44.2	
Pro Air, mL	2.5		2.5		2.5		1.9		2.5		2.5		1.9	
Total Water, kg	8.30		7.75		7.35		6.80		7.80		7.00		6.65	
Fresh Concrete Test Results														
Density, kg/m3	2357	2364	2357	2354	2336	2354	2377	2370	2354	2340	2346	2371	2396	2386
Yield, L	49.6	49.4	49.0	49.1	49.1	48.7	47.8	47.9	49.0	49.3	48.6	48.1	47.2	47.4
Cement, kg/m3	312.5	313.8	316.3	315.7	315.8	318.2	324.3	323.6	316.1	314.3	319.0	322.5	328.4	327.0
Effective W/C Ratio	0.465	0.465	0.429	0.429	0.403	0.403	0.368	0.368	0.432	0.432	0.381	0.381	0.358	0.358
Slump, mm	70	70	75	75	80	80	85	80	75	85	85	80	90	90
Air Content	5.7	6.0	6.0	6.3	6.8	6.0	6.0	6.0	6.3	6.7	6.8	6.4	5.5	5.7
Strength Test Results														
Compressive Strength, MPa 1 d	18.5		19.7		20.8		22.8		17.5		15.4		14.6	
3 d	26.1		27.2		27.9		31.7		25.3		24.9		23.1	
7 d	31.2		32.6		33.1		39.8		30.8		32.1		32.5	
28 d	39.0		39.7		43.1		48.8		39.6		44.0		44.6	
90 d	45.1		46.5		51.1		54.1		45.9		53.6		48.9	
Splitting Tensile Strength, MPa 1 d	1.8		2.2		2.4		2.5		1.9		1.6		1.6	
3 d	2.6		3.1		3.4		3.5		2.8		2.5		2.3	
7 d	3.5		3.5		3.9		4.2		3.0		3.5		3.5	
28 d	3.8		4.1		4.4		4.7		3.7		4.5		3.9	
90 d	4.2		4.9		5.0		4.8		4.7		4.8		4.5	

TABLE E. MIX PROPORTIONS, FRESH CONCRETE AND STRENGTH TEST RESULTS
20 MPa CONCRETE, CEMENT B

	Control		St. Clair Fly Ash						Thunder Bay Fly Ash					
MIX NUMBER	L760/86		L778/86		L794/86		L700/87		L771/86		L790/86		L803/86	
FLY ASH, %, by mass of total cementitious material	0		10		25		40		10		25		40	
Mix Proportions per 50 L batch														
Cement, kg	15.5		14.0		11.6		9.3		14.0		11.6		9.3	
Fly Ash, kg	-		1.5		3.9		6.2		1.5		3.9		6.2	
Coarse Aggregate, kg	53.2		53.2		53.2		53.2		53.2		53.2		53.2	
Fine Aggregate, kg	39.8		39.0		38.6		38.0		38.9		38.3		37.8	
PDA 25XL, mL	44.2		44.2		44.2		44.2		44.2		44.2		44.2	
Pro Air, mL	2.5		2.5		2.5		1.9		2.5		2.5		2.5	
Total Water, kg	8.50		8.20		8.30		7.20		8.00		7.85		7.05	
Fresh Concrete Test Results														
Density, kg/m3	2368	2329	2343	2336	2332	2325	2371	2364	2346	2371	2336	2339	2339	2368
Yield, L	49.4	50.2	49.5	49.6	49.6	49.7	48.0	48.2	49.3	48.8	49.2	49.1	48.5	48.0
Cement, kg/m3	313.7	308.5	313.1	312.5	312.5	311.9	322.9	321.6	314.6	318.0	315.2	315.7	319.6	322.9
Effective W/C Ratio	0.477	0.477	0.458	0.458	0.464	0.464	0.394	0.394	0.445	0.445	0.435	0.435	0.384	0.384
Slump, mm	70	80	80	75	75	85	75	70	80	70	85	85	90	80
Air Content, %	6.1	6.4	6.2	6.3	6.7	7.0	6.3	6.5	6.5	5.6	6.6	6.2	7.0	6.5
Strength Test Results														
Compressive Strength, MPa 1 d	19.7		18.9		17.0		16.3		17.1		15.0		13.7	
3 d	26.5		25.4		22.2		25.0		25.3		22.0		22.6	
7 d	31.4		30.4		26.9		30.1		30.9		26.9		31.1	
28 d	38.1		39.3		35.5		36.5		40.4		39.3		45.0	
90 d	49.9		46.2		43.9		42.2		49.8		47.9		52.9	
Splitting Tensile Strength, MPa 1 d	2.0		2.2		1.7		1.7		1.9		1.7		1.4	
3 d	3.0		2.9		2.7		2.9		2.4		2.5		2.3	
7 d	3.2		3.2		2.8		3.2		3.1		2.9		3.3	
28 d	3.8		3.6		3.4		3.8		4.1		3.8		4.4	
90 d	4.2		4.8		4.4		4.2		4.8		4.2		4.4	

TABLE F. MIX PROPORTIONS, FRESH CONCRETE AND STRENGTH TEST RESULTS
35 MPa CONCRETE, CEMENT A

	Control	St. Clair Fly Ash			Thunder Bay Fly Ash		
MIX NUMBER	L763/86	L787/86	L797/86	L713/87	L779/86	L795/86	L710/87
FLY ASH, %, by mass of total cementitious material	0	10	25	40	10	25	40
Mix Proportions per 50 L batch							
Cement, kg	20.8	18.7	15.6	12.5	18.7	15.6	12.5
Fly Ash, kg	-	2.1	5.2	8.3	2.1	5.2	8.3
Coarse Aggregate, kg	53.2	53.2	53.2	53.2	53.2	53.2	53.2
Fine Aggregate, kg	34.8	34.3	33.7	33.2	34.3	33.5	32.8
PDA 25XL, mL	59.3	59.3	59.3	59.3	59.3	59.3	59.3
Pro Air, mL	4.2	4.2	4.2	2.5	5.0	3.3	3.0
Total Water, kg	9.00	8.30	7.80/8.10	7.15	8.25	7.80	6.80
Fresh Concrete Test Results							
Density, kg/m3	2375 2368	2354 2354	2371 2350	2391 2379	2361 2364	2375 2354	2387 2380
Yield, L	49.6 49.7	49.5 49.5	48.7 49.3	47.8 48.1	49.4 49.3	48.5 49.0	47.6 47.7
Cement, kg/m3	419.4 418.5	419.9 419.9	427.1 421.9	435.2 432.4	421.3 421.9	428.9 424.5	437.0 436.1
Effective W/C Ratio	0.380 0.380	0.346 0.346	0.322 0.336	0.291 0.291	0.344 0.344	0.322 0.322	0.274 0.274
Slump, mm	80 75	90 90	85 90	80 85	85 75	90 90	90 90
Air Content, %	5.4 5.6	6.4 6.4	6.0 6.9	5.2 5.5	5.8 5.8	5.7 6.2	5.2 5.5
Strength Test Results							
Compressive Strength, MPa 1 d	28.9	26.6	28.3	29.2	27.7	25.4	19.1
3 d	34.2	34.0	36.2	41.0	33.2	32.0	33.4
7 d	37.7	38.7	41.7	49.4	37.9	38.4	44.7
28 d	45.8	46.6	50.7	56.3	47.9	52.4	56.7
90 d	57.1	55.2	60.5	63.9	58.4	61.0	66.0
Splitting Tensile Strength, MPa 1 d	2.7	2.4	3.2	2.9	2.8	2.9	1.9
3 d	3.3	3.6	4.0	3.9	3.4	3.4	3.1
7 d	3.5	3.6	4.2	4.6	3.7	3.7	3.8
28 d	4.2	4.2	4.1	5.0	4.8	4.7	4.9
90 d	4.9	4.9	5.3	5.5	5.3	5.3	5.2

TABLE G. MIX PROPORTIONS, FRESH CONCRETE AND STRENGTH TEST RESULTS
35 MPa CONCRETE, CEMENT B

	Control		St. Clair Fly Ash						Thunder Bay Fly Ash					
MIX NUMBER	L764/86		L788/86		L800/86		L715/87		L786/86		L796/86		L707/87	
FLY ASH, %, by mass of total cementitious material	0		10		25		40		10		25		40	
Mix Proportions per 50 L batch														
Cement, kg	20.8		18.7		15.6		12.5		18.7		15.6		12.5	
Fly Ash, kg	-		2.1		5.2		8.3		2.1		5.2		8.3	
Coarse Aggregate, kg	53.2		53.2		53.2		53.2		53.2		53.2		53.2	
Fine Aggregate, kg	34.8		34.3		33.7		33.2		34.3		33.5		32.8	
PDA 25XL, mL	59.3		59.3		59.3		59.3		59.3		59.3		59.3	
Pro Air, mL	4.2		4.2		3.3		3.3		3.3		3.3		2.5	
Total Water, kg	9.20		9.30		8.55		7.90		9.50		8.20		8.00	
Fresh Concrete Test Results														
Density, kg/m3	2332	2325	2350	2346	2361	2354	2377	2384	2382	2350	2368	2364	2352	2341
Yield, L	50.6	50.8	50.0	50.1	49.2	49.4	48.3	48.3	49.5	50.1	48.9	48.9	48.8	49.0
Cement, kg/m3	411.1	409.9	415.7	415.0	422.8	421.1	430.6	430.6	420.6	414.9	425.4	425.4	426.2	424.5
Effective W/C Ratio	0.389	0.389	0.394	0.394	0.358	0.358	0.327	0.327	0.404	0.404	0.341	0.341	0.332	0.332
Slump, mm	80	85	85	80	75	75	85	80	75	85	80	80	85	90
Air Content, %	6.5	6.3	5.4	5.4	5.6	5.6	5.1	5.2	5.5	5.9	5.5	5.4	5.5	6.0
Strength Test Results														
Compressive Strength, MPa 1 d	22.6		23.0		23.3		23.0		22.6		22.3		16.7	
3 d	30.2		29.9		29.5		32.4		29.7		30.7		25.1	
7 d	35.3		34.5		34.0		38.4		35.6		37.3		35.4	
28 d	43.5		43.5		44.8		45.6		45.8		50.5		49.7	
90 d	52.6		51.5		54.5		51.7		55.0		58.0		55.7	
Splitting Tensile Strength, MPa 1 d	2.4		2.4		2.6		2.4		2.3		2.5		1.7	
3 d	3.0		3.3		3.2		3.1		3.0		3.0		2.6	
7 d	3.4		3.2		3.5		3.6		3.3		3.4		3.7	
28 d	4.0		4.2		4.5		4.3		4.3		3.8		4.2	
90 d	4.4		4.7		5.0		4.8		4.9		4.7		4.9	

TABLE H. FREEZE THAW RESISTANCE, SALT SCALING RESISTANCE, CHLORIDE PERMEABILITY AND SHRINKAGE. 20 MPa CONCRETE, CEMENT A

	Control	St. Clair Fly Ash			Thunder Bay Fly Ash		
MIX NUMBER	L762/86	L777/86	L791/86	L703/87	L765/86	L789/86	L805/86
FLY ASH, %, by mass of total cementitious material	0	10	25	40	10	25	40
Freeze Thaw Resistance							
Durability factor, %	96.5	93.5	100.8	100.3	98.0	98.8	80.4
Mass Loss, %	-0.80	-0.31	-0.21	-0.04	-0.23	-0.18	+0.13
Expansion, %	+0.016	-0.007	+0.019	+0.016	+0.015	+0.008	+0.118
Salt Scaling Resistance							
Mass Loss, kg/m2 at							
5 cycles	0.306	0.373	0.388	0.924	0.912	0.255	1.427
10 "	0.493	0.567	0.527	1.509	1.048	0.531	1.861
15 "	0.601	0.648	0.707	1.929	1.122	0.646	2.130
20 "	0.634	0.780	0.865	2.326	1.170	0.853	2.331
25 "	0.679	0.913	1.236	2.582	1.223	1.267	2.538
30 "	0.736	1.073	1.812	2.839	1.260	1.497	2.752
35 "	0.750	1.194	2.127	3.121	1.286	1.668	3.002
40 "	0.777	1.284	2.372	3.309	1.312	1.887	3.235
45 "	0.848	1.412	2.491	3.601	1.346	2.112	3.448
50 "	0.937	1.601	2.616	3.947	1.386	4.587	3.697
Shrinkage							
Change in Length, % after							
28 d moist	+0.002	+0.003	+0.003	+0.002	+0.002	+0.001	+0.005
1 d dry	-0.004	+0.002	+0.002	-0.002	-0.003	0.000	+0.001
3 d "	-0.007	no test	no test	-0.005	-0.008	no test	-0.001
7 d "	-0.011	-0.010	-0.001	-0.008	-0.011	-0.008	-0.003
28 d "	-0.030	-0.026	-0.015	-0.014	-0.024	-0.018	-0.014
90 d "	-0.042	-0.035	-0.029	-0.033	-0.036	-0.030	-0.028
Chloride Permeability							
Chloride Permeability, Coulombs	3780	3147	1647	1112	2520	1203	648
Air Void System (Scaling Slab, Vertical Section)*							
Air Content, %	4.8(2.7)	3.2(2.2)	4.2(3.2)	4.3(2.7)	4.1(3.0)	3.7(2.6)	3.7(2.8)
Specific Surface, mm-1	19.2(32.5)	22.5(31.2)	29.8(38.5)	29.0(44.1)	28.1(37.3)	24.7(34.3)	30.9(40.3)
Spacing Factor, mm	0.246(0.188)	0.253(0.214)	0.169(0.148)	0.172(0.138)	0.181(0.157)	0.214(0.181)	0.172(0.149)

* The figures in brackets include only voids with a chord length lower than 1 mm.

TABLE I. FREEZE THAW RESISTANCE, SALT SCALING RESISTANCE, CHLORIDE PERMEABILITY AND SHRINKAGE. 20 MPa CONCRETE, CEMENT B

	Control	St. Clair Fly Ash			Thunder Bay Fly Ash		
MIX NUMBER	L760/86	L778/86	L794/86	L700/87	L771/86	L790/86	L803/86
FLY ASH ,%, by mass of total cementitious material	0	10	25	40	10	25	40
Freeze Thaw Resistance							
Durability factor, %	95.4	97.7	103.7	97.2	97.3	98.3	111.0
Mass Loss, %	-1.04	-0.26	+0.03	-0.11	-2.50	-0.25	+0.01
Expansion, %	+0.012	+0.015	+0.027	+0.024	+0.028	+0.016	+0.015
Salt Scaling Resistance							
Mass Loss, kg/m2 at							
5 cycles	0.739	0.244	1.444	1.384	0.096	1.176	0.472
10 "	0.850	0.390	1.867	2.018	0.300	1.374	0.756
15 "	0.920	0.477	2.020	2.183	0.393	1.424	1.056
20 "	0.983	0.673	2.209	2.289	0.468	1.661	1.485
25 "	1.132	0.848	2.316	2.443	0.566	1.750	1.920
30 "	1.198	1.002	2.378	2.599	0.624	1.850	2.230
35 "	1.265	1.090	2.503	2.784	0.671	2.209	2.382
40 "	1.293	1.325	2.740	2.958	0.776	2.464	2.616
45 "	1.320	1.528	2.873	3.181	0.877	2.610	2.853
50 "	1.444	1.672	3.025	3.442	0.995	2.688	3.067
Shrinkage							
Change in Length, % after							
28 d moist	+0.002	+0.006	+0.006	+0.002	+0.004	+0.003	+0.001
1 d dry	+0.001	+0.003	+0.003	-0.001	+0.001	0.000	+0.006
3 d "	-0.007	no test	-0.001	-0.003	-0.003	no test	+0.002
7 d "	-0.014	-0.012	-0.002	-0.005	-0.009	-0.010	-0.002
28 d "	-0.032	-0.029	-0.019	-0.012	-0.026	-0.019	-0.011
90 d "	-0.046	-0.045	-0.034	-0.031	-0.046	-0.029	-0.023
Chloride Permeability							
Chloride Permeability, Coulombs	4067	3826	2183	1347	3316	1704	988
Air Void System (Scaling Slab, Vertical Section)*							
Air Content, %	4.0(3.3)	3.8(2.8)	5.5(3.8)	3.9(2.5)	3.2(2.4)	4.1(2.9)	
Specific Surface, mm-1	29.1(35.0)	27.8(36.4)	27.9(39.2)	31.5(47.2)	22.0(28.6)	26.9(37.2)	
Spacing Factor, mm	0.176(0.160)	0.190(0.165)	0.160(0.134)	0.165(0.134)	0.257(0.224)	0.188(0.159)	

* The figures in brackets include only voids with a chord length lower than 1 mm.

TABLE J. FREEZE THAW RESISTANCE, SALT SCALING RESISTANCE, CHLORIDE PERMEABILITY AND SHRINKAGE. 35 MPa CONCRETE, CEMENT A

	Control	St. Clair Fly Ash			Thunder Bay Fly Ash		
MIX NUMBER	L763/86	L787/86	L797/86	L713/87	L779/86	L795/86	L710/87
FLY ASH, %, by mass of total cementitious material	0	10	25	40	10	25	40
Freeze Thaw Resistance							
Durability factor, %	97.4	105.1	103.2	101.8	96.4	106.7	94.2
Mass Loss, %	-0.39	-0.10	-0.19	-0.05	-0.38	+0.05	+0.13
Expansion, %	+0.019	+0.017	+0.031	+0.018	+0.013	+0.028	+0.052
Salt Scaling Resistance							
Mass Loss, kg/m2 at							
5 cycles	0.275	0.058	0.267	0.397	0.066	0.192	0.261
10 "	0.326	0.102	0.717	0.775	0.114	0.339	0.512
15 "	0.349	0.117	1.420	1.022	0.185	0.800	1.288
20 "	0.362	0.139	1.581	1.255	0.296	1.200	1.933
25 "	0.377	0.195	1.760	1.495	0.408	1.462	2.375
30 "	0.425	0.275	1.915	1.797	0.510	1.765	2.748
35 "	0.476	0.392	2.146	2.157	0.709	2.042	3.231
40 "	0.567	0.504	2.346	2.459	0.993	2.259	3.653
45 "	0.694	0.607	2.508	2.725	1.264	2.441	3.871
50 "	0.771	0.676	2.681	2.951	1.482	2.634	4.066
Shrinkage							
Change in Length, % after							
28 d moist	+0.006	0.000*	+0.013	+0.006	+0.004**	+0.009	+0.002
1 d dry	+0.003	-0.001	+0.008	+0.003	+0.007	+0.006	+0.002
3 d "	-0.008	0.000	-0.002	+0.004	+0.004	+0.005	-0.003
7 d "	-0.013	-0.002	-0.002	+0.001	+0.005	-0.003	-0.003
28 d "	-0.022	-0.024	-0.018	-0.015	-0.016	-0.014	-0.021
90 d "	-0.035	-0.032	-0.035	-0.024	-0.031	-0.031	-0.027
Chloride Permeability							
Chloride Permeability, Coulombs	3218	2598	1171	680	2955	997	469
Air Void System (Scaling Slab, Vertical Section)* **							
Air Content, %	3.0(2.3)		3.9(2.6)				
Specific Surface, mm-1	29.9(38.8)		33.5(49.0)				
Spacing Factor, mm	0.195(0.170)		0.154(0.126)				

* Reading taken after 63 d in the moisture room. Calculations are based on this reading

** 84 d in moisture room

*** The figures in brackets include only voids with a chord length lower than 1 mm.

TABLE K. FREEZE THAW RESISTANCE, SALT SCALING RESISTANCE, CHLORIDE PERMEABILITY AND SHRINKAGE. 35 MPa CONCRETE, CEMENT B

	Control	St. Clair Fly Ash			Thunder Bay Fly Ash		
MIX NUMBER	L764/86	L788/86	L800/86	L715/87	L786/86	L796/86	L707/87
FLY ASH, %, by mass of total cementitious material	0	10	25	40	10	25	40
Freeze Thaw Resistance							
Durability factor, %	96.7	79.6	100.2	103.8	102.8	106.1	99.7
Mass Loss, %	-0.60	-0.84	-0.12	+0.01	-1.39	+0.08	-0.02
Expansion, %	+0.027	+0.091	+0.024	+0.026	+0.033	+0.036	+0.024
Salt Scaling Resistance							
Mass Loss, kg/m2 at							
5 cycles	0.083	0.472	1.093	0.159	0.219	0.306	1.805
10 "	0.202	0.607	1.383	0.301	0.292	0.513	2.139
15 "	0.222	0.702	1.584	0.425	0.406	0.673	2.491
20 "	0.248	0.822	1.910	0.529	0.481	1.230	2.597
25 "	0.267	0.954	2.127	0.736	0.614	1.650	3.150
30 "	0.294	1.095	2.385	1.484	0.822	1.829	3.588
35 "	0.307	1.205	2.616	2.122	1.000	1.969	3.970
40 "	0.332	1.308	2.814	2.421	1.138	2.123	4.394
45 "	0.373	1.414	3.018	2.703	1.275	2.311	4.782
50 "	0.467	1.509	3.189	2.998	1.435	2.500	5.102
Shrinkage							
Change in Length, % after							
28 d moist	+0.002	+0.007	+0.007	+0.011	+0.003	-0.004	-0.001
1 d dry	-0.004	+0.005	+0.004	+0.010	-0.002	-0.004	-0.003
3 d "	-0.006	not tested	+0.002	+0.005	not tested	-0.005	-0.015
7 d "	-0.020	-0.003	-0.004	-0.003	-0.012	-0.008	-0.020
28 d "	-0.035	-0.016	-0.020	-0.018	-0.030	-0.027	-0.026
90 d "	-0.051	-0.040	-0.042	-0.022	-0.043	-0.035	-0.038
Chloride Permeability							
Chloride Permeability, Coulombs	4092	5580	1829	736	3519	1085	775
Air Void System (Scaling Slab, Vertical Section)*							
Air Content, %	3.8(2.9)	4.4(2.9)				3.6(2.0)	
Specific Surface, mm-1	31.4(39.8)	25.6(38.3)				26.3(45.2)	
Spacing Factor, mm	0.168(0.149)	0.193(0.156)				0.205(0.154)	

* The figures in brackets include only voids with a chord length lower than 1 mm.

TABLE L: MIX PROPORTIONS AND TEST RESULTS
FIELD PROJECT

PROPERTIES	CONTROL MIX CEMENT 86-L-15 C		TEST MIX CEMENT 86-L-15 C FLY ASH "C" 86-L-14	
Mix proportions per cubic metre of concrete				
Cement, kg	355		267	
Fly Ash "C", kg	-		88	
Coarse Aggregate, kg (Preston S. & G., 20mm)	1130		1130	
Fine Aggregate, kg (Warren Bitulithic)	737		737	
WRDA 82, mL per 100 kg cement	280		280	
Darex AEA, mL	sufficient to entrain 7±1.5% air			
Total Water, kg (approx.)	145		145	
Test Results - Fresh Concrete				
Slump, mm	80	75	80	70
Air Content, %	6.5	6.0	7.1	8.2
Concrete Temperature, °C	22	20	26	24
Test Results - Hardened Concrete				
Compressive Strength, MPa				
1 d	20.7	16.9	15.0	18.3
3 d	31.4	29.5	19.7	22.8
7 d	34.7	32.5	24.2	26.3
28 d	39.4	37.8	28.5	33.5
Freeze - Thaw Resistance				
- durability factor, %	92.0	93.0	93.3	94.0
- mass loss, %	0.95	1.40	1.41	0.83
- expansion, %	0.015	0.017	0.011	0.015
Salt Scaling Resistance				
-mass loss, kg/m2 at				
5 cycles	0.027	0.024	0.484	0.176
10 cycles	0.040	0.062	0.642	0.270
15 cycles	0.063	0.088	0.785	0.419
20 cycles	0.087	0.111	1.091	0.579
25 cycles	0.143	0.149	1.385	0.852
30 cycles	0.169	0.175	1.504	0.972
35 cycles	0.198	0.202	1.649	1.109
40 cycles	0.225	0.237	1.784	1.251
45 cycles	0.247	0.287	1.889	1.381
50 cycles	0.300	0.312	1.964	1.464

TABLE M: COMPARISON OF TEST RESULTS OBTAINED ON FIELD SAMPLES

Sample Number	Date of Concrete Placement	Panel Number	Fresh Concrete Test Results MTC			28 d Compressive Strength MPa, Tested by		Core strength, MPa Tested by Peto MacCallum (Age 136-140 d)	Impact hammer Compressive Str., MPa Tested by CCL Ltd. (Age 124-128 d)
			Air Content (%)	Slump (mm)	Temperature (°C)	MTC Downsview	Peto MacCallum Kitchener		
FLY ASH CONCRETE - TEST MIX									
267	86/05/30	(2,4,6,8,10)	6.9	70	24	-	26.6	38.9 (37.1-40.6)*	Avg of 5 panels =27.3 (23.5-31.7)*
274	86/06/04	12	7.1	80	26	28.5	27.5	38.4 (37.4-39.0)*	
-		16 (12,14,16,18,20)	8.2	70	24	33.5	-	-	
100 % PORTLAND CEMENT CONCRETE - CONTROL MIX									
270	86/06/02	5	6.5	80	22	39.4	42.7	45.4 (40.9-48.4)*	Avg of 5 panels =27.8 (23.1-34.5)*
-	-	9 (5,7,9,11)	6.0	70	20	37.8	-	-	
271	86/06/03	(3,13,15,17)	7.7	75	20	-	37.9	38.7 (37.4-40.6)*	
275	86/06/05	(19,21,23)	6.0	80	21	-	42.3	-	

* range of core or impact hammer strengths

TABLE N: AIR VOID SYSTEM TEST RESULTS OBTAINED BY MTC AND CCL LTD. ON FIELD CONCRETE

Sample	Tested by MTC on Slabs								Tested by CCL Ltd. on Cores			
	Vertical Section				Top Surface							
Number	A, %	S, mm-1	P, %	L, mm	A, %	S, mm-1	P, %	L, mm	A, %	S, mm-1	P, %	L, mm
FLY ASH CONCRETE - TEST MIX												
267	7.5	38.2	21.9	0.077	8.1	37.6	25.2	0.083	6.5	26.4	26.9	0.157
-	7.3	42.9	22.1	0.071	7.8	44.3	29.5	0.085	-	-	-	-
274	-	-	-	-	-	-	-	-	4.8	40.6	29.9	0.126
100 % PORTLAND CEMENT CONCRETE - CONTROL MIX												
270	6.3	32.8	24.0	0.116	5.5	39.3	31.9	0.126	5.8	31.6	31.1	0.151
-	7.7	33.3	23.9	0.093	11.0	28.8	27.5	0.090	-	-	-	-
271	-	-	-	-	-	-	-	-	7.9	32.0	28.3	0.111

Note: Air void system determined by the Modified Point Count Method (ASTM C 457)

A = air content
S = specific surface
P = paste content
L = spacing factor

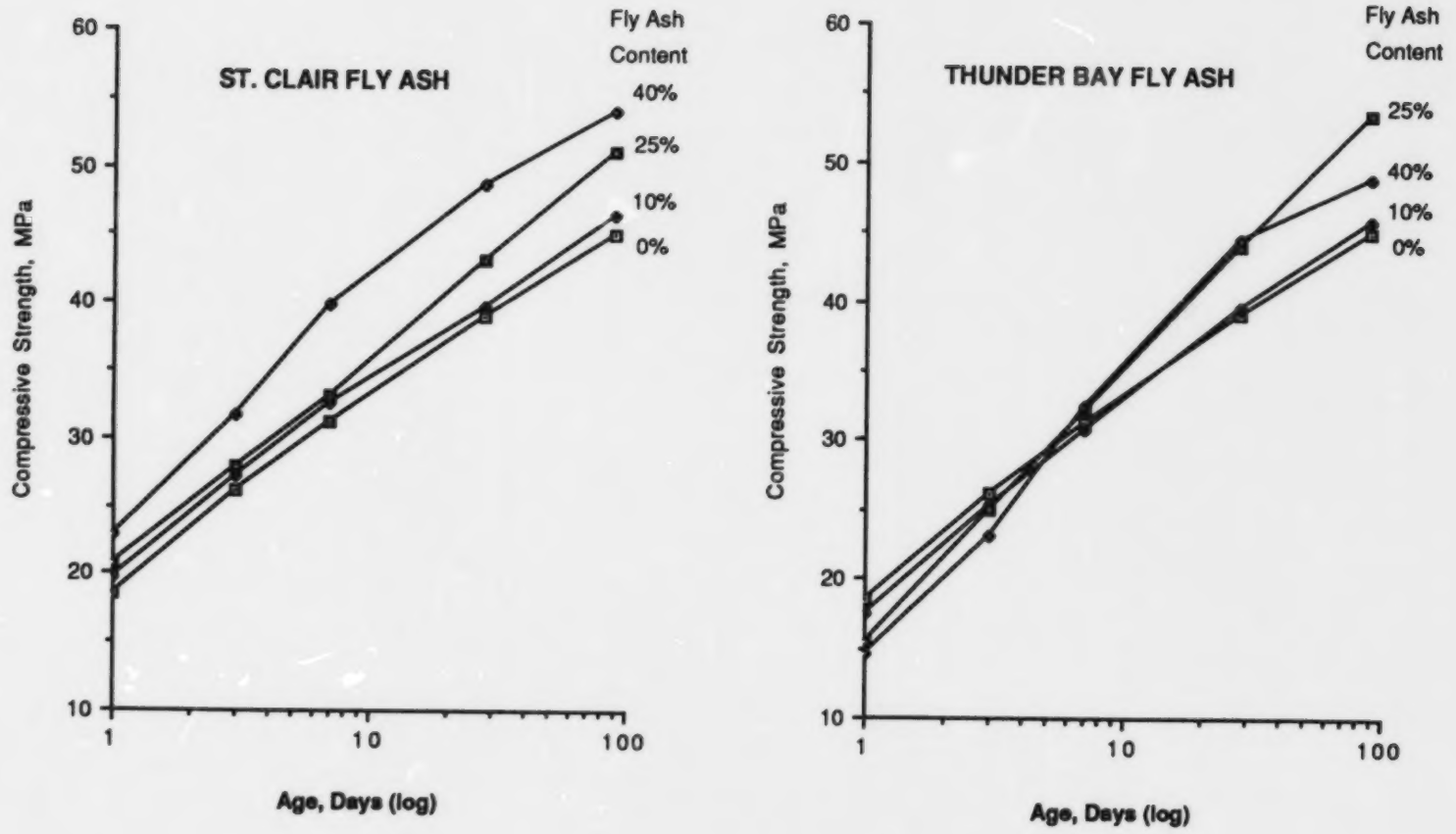


Figure 1. Compressive Strength Test Results - 20 MPa Concrete, Cement A (Woodstock)

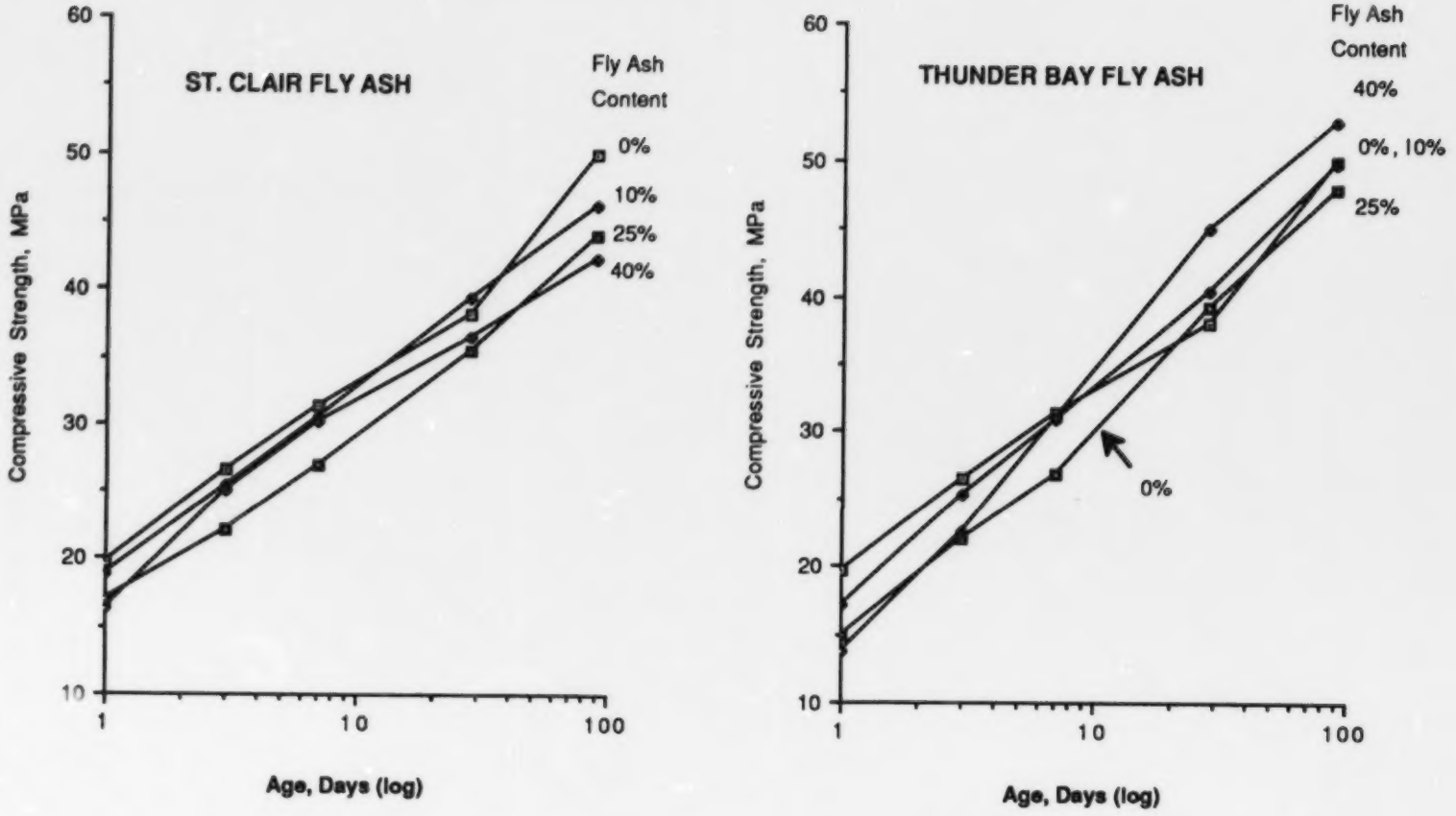


Figure 2. Compressive Strength Test Results - 20 MPa Concrete, Cement B (Clarkson)

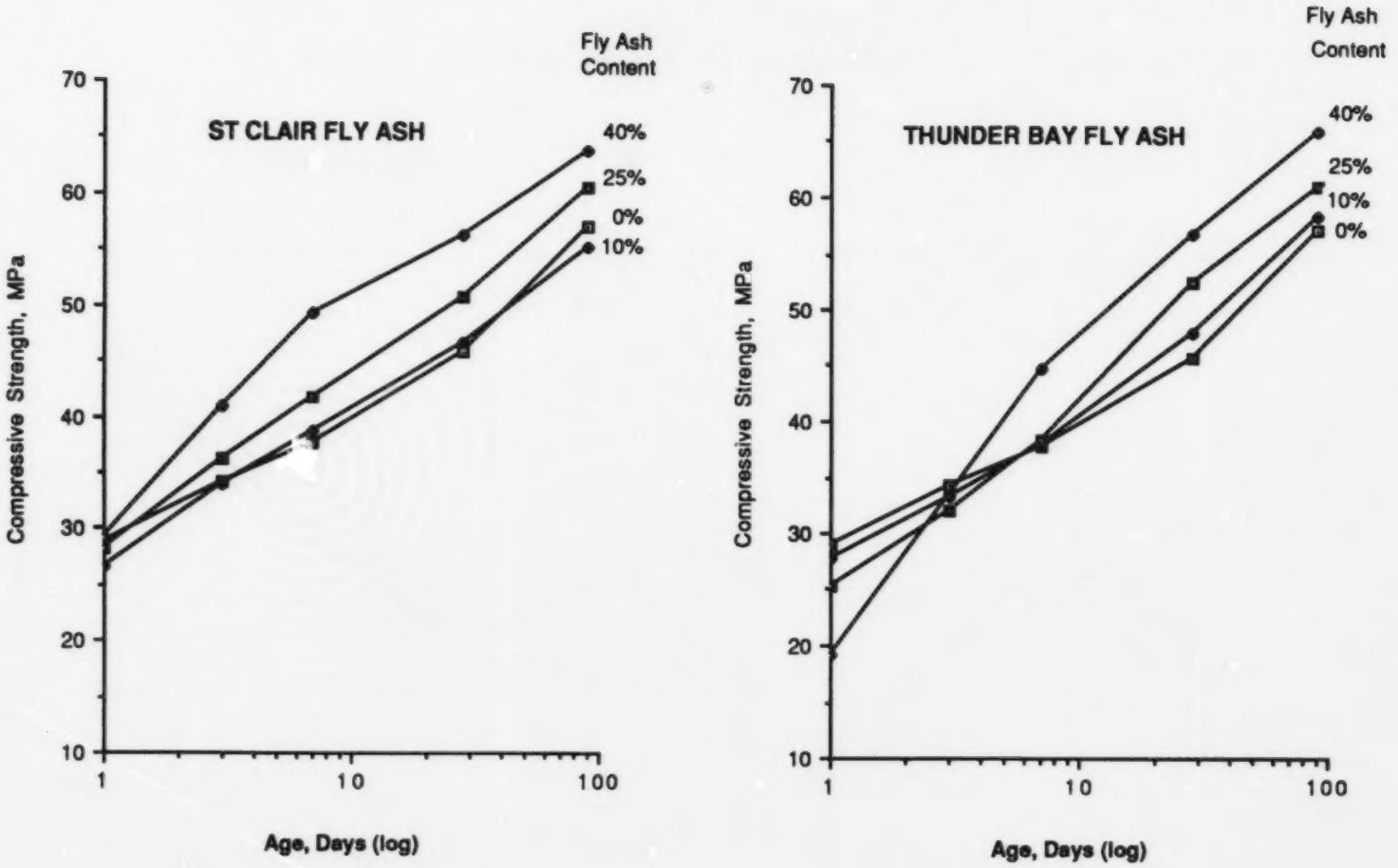


Figure 3. Compressive Strength Test Results - 35 MPa Concrete, Cement A

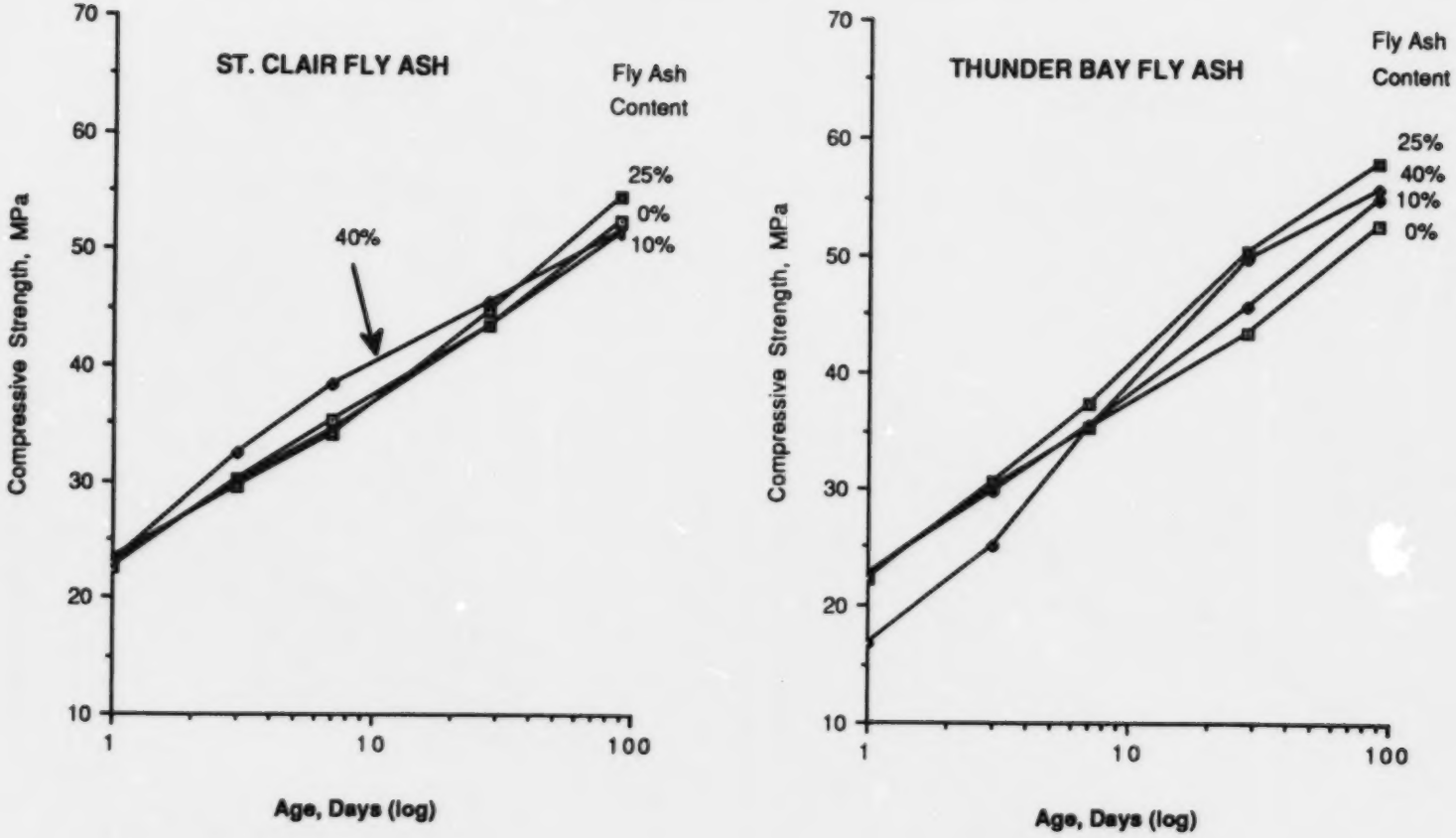


Figure 4. Compressive Strength Test Results - 35 MPa Concrete, Cement B

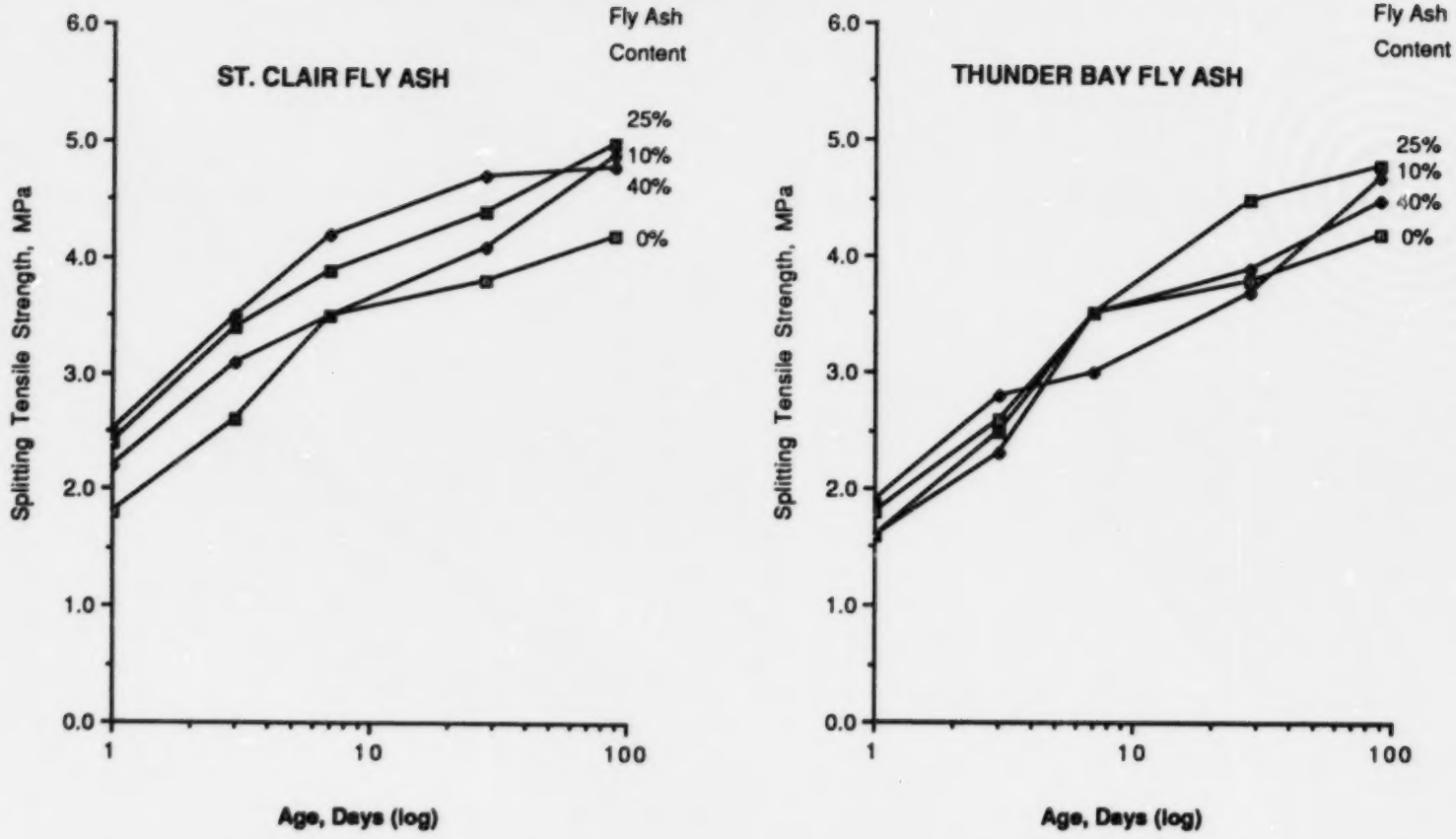


Figure 5. Splitting Tensile Strength Test Results
20 MPa Concrete, Cement A

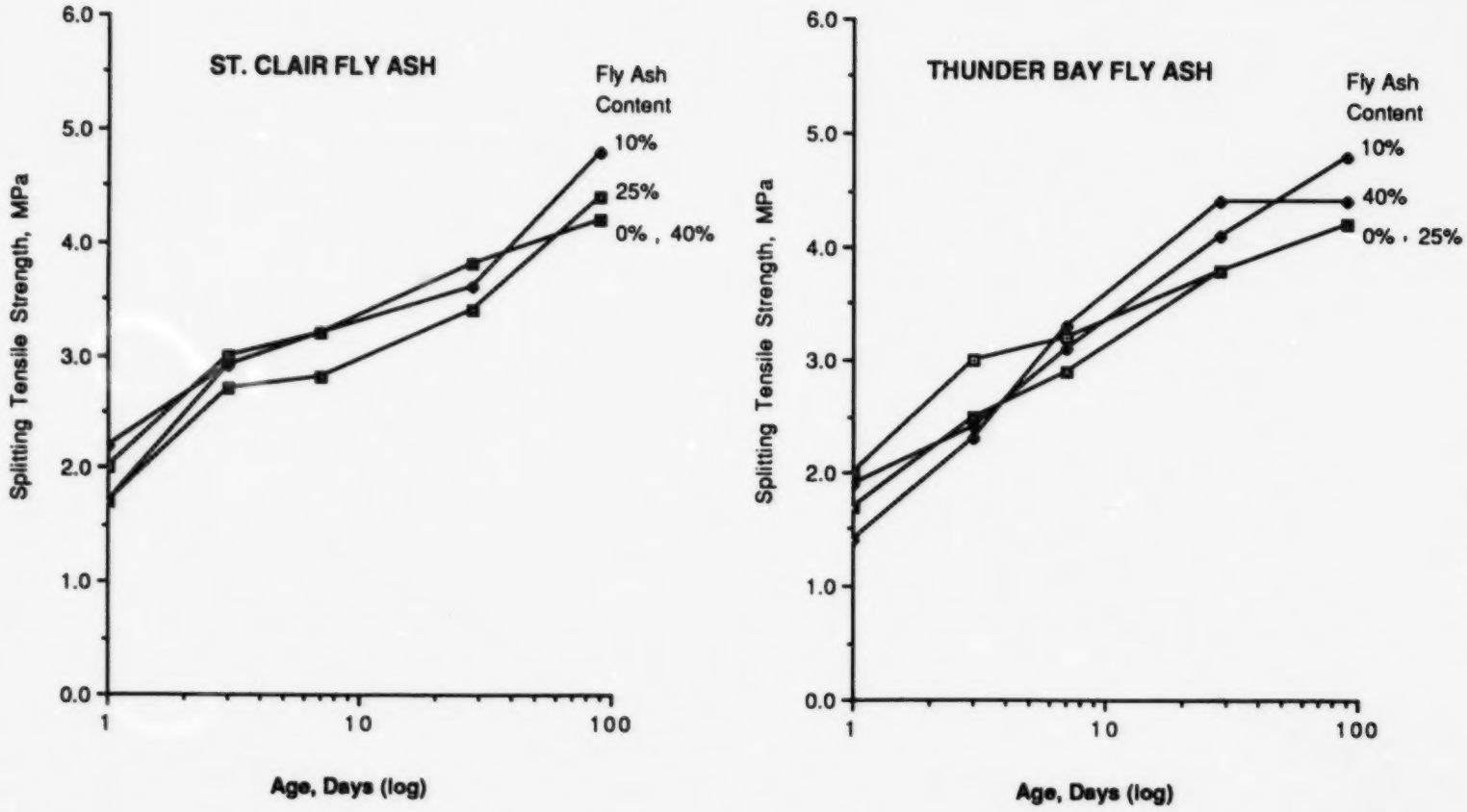


Figure 6. Splitting Tensile Strength Test Results
20 MPa Concrete, Cement B

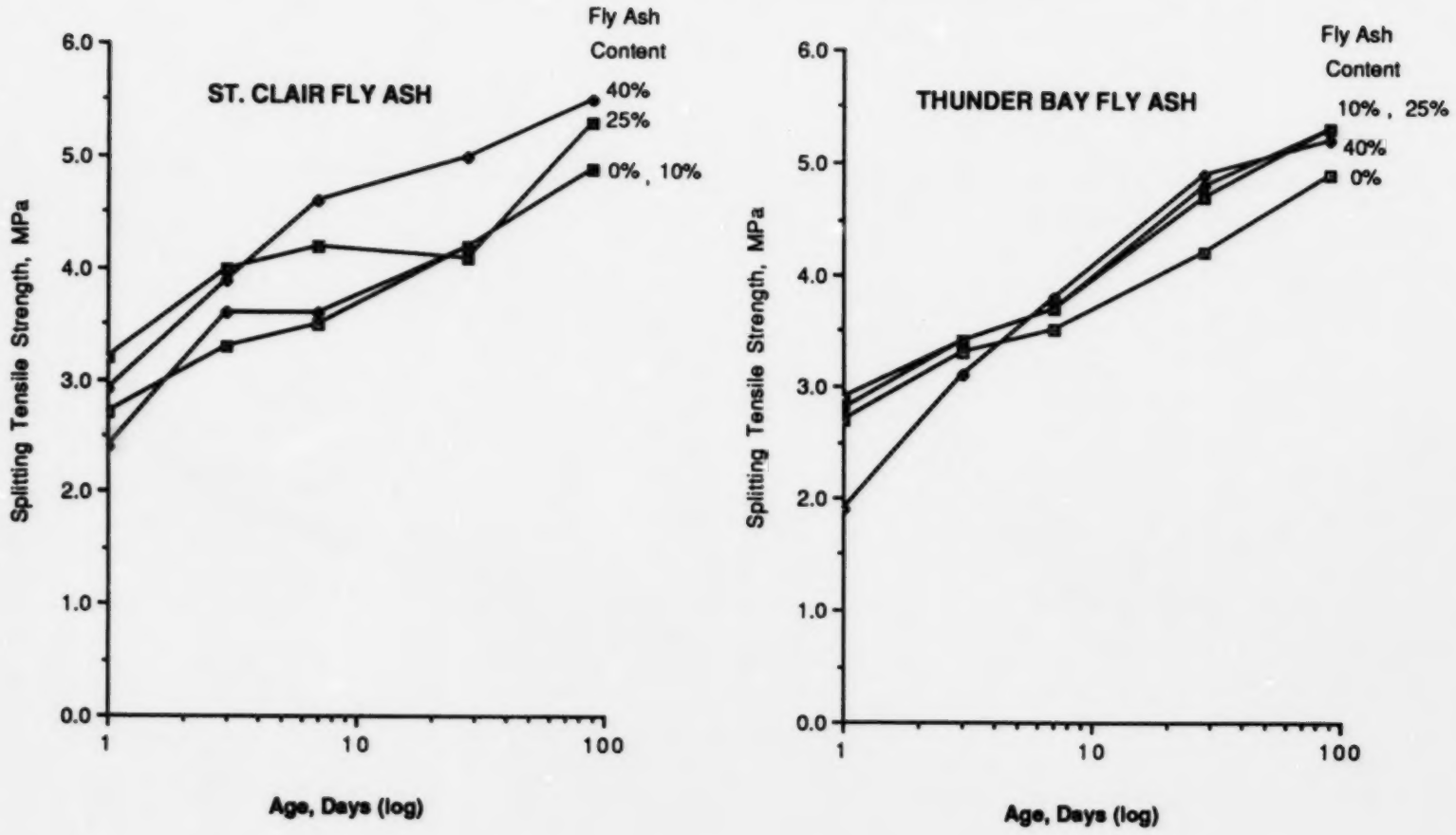


Figure 7. Splitting Tensile Strength Test Results
35 MPa Concrete, Cement A

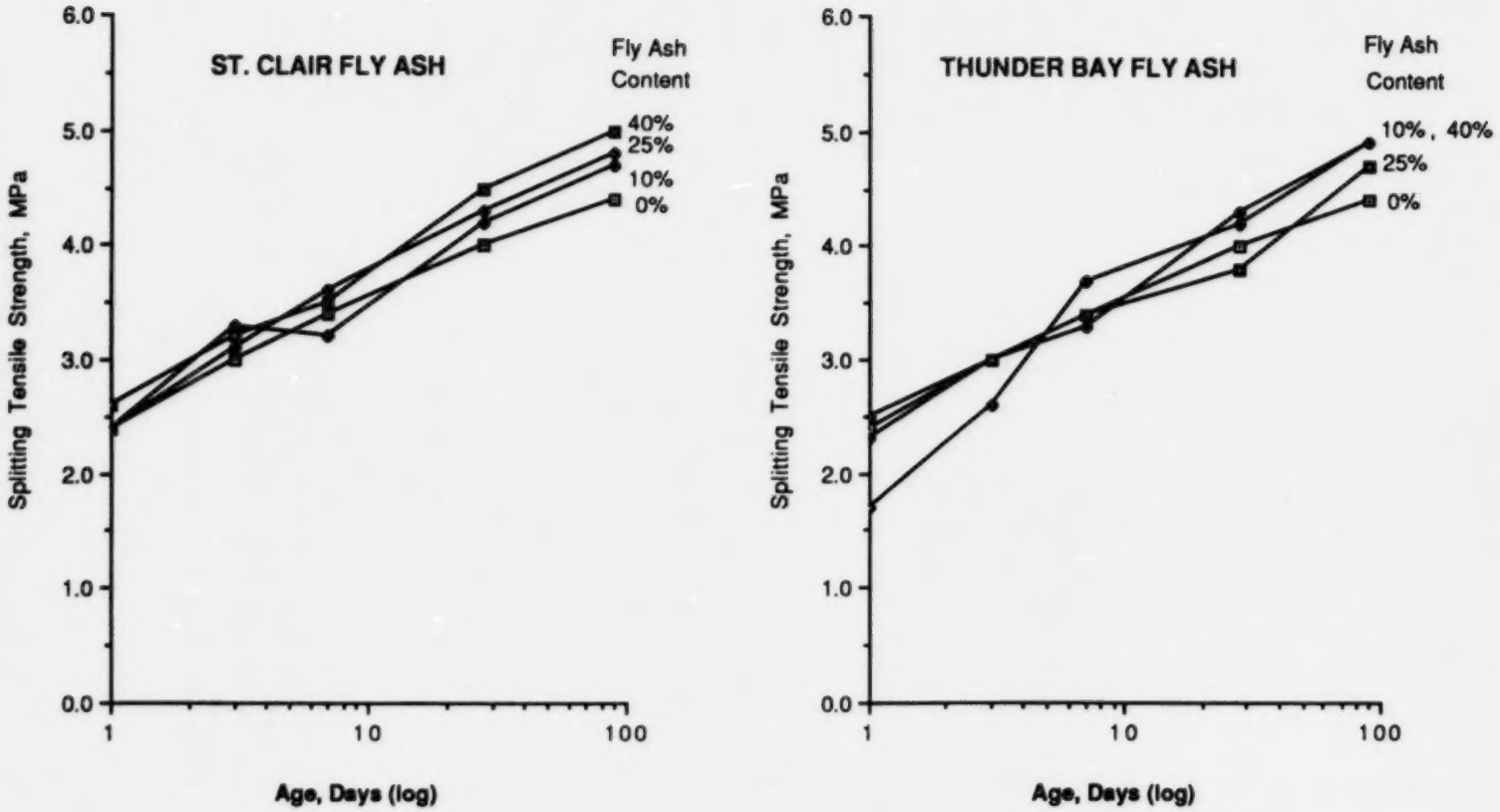
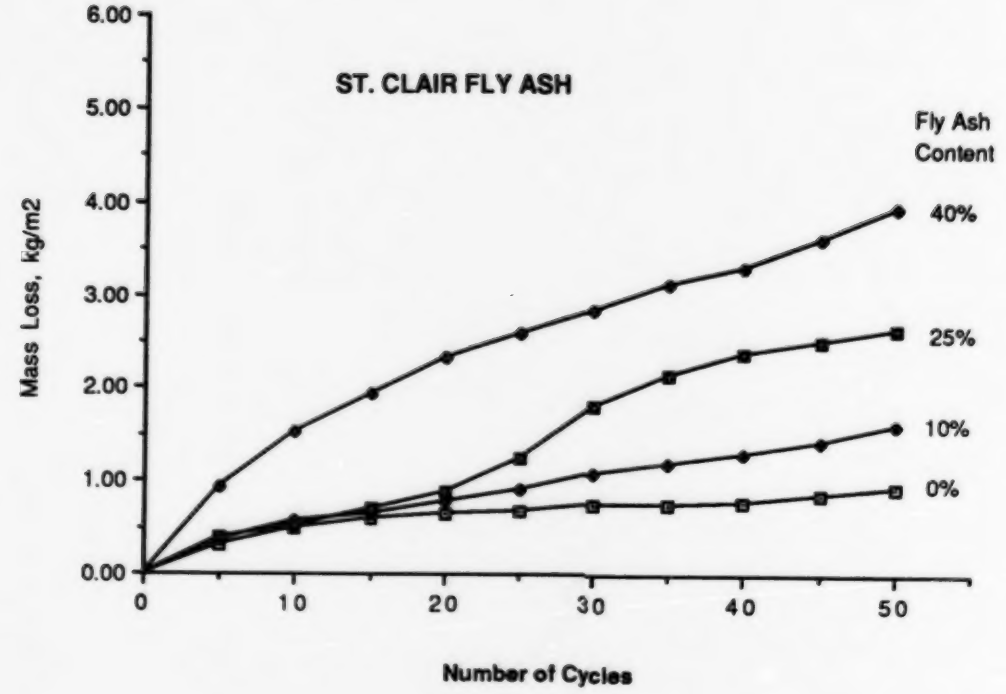


Figure 8. Splitting Tensile Strength Test Results
35 MPa Concrete, Cement B



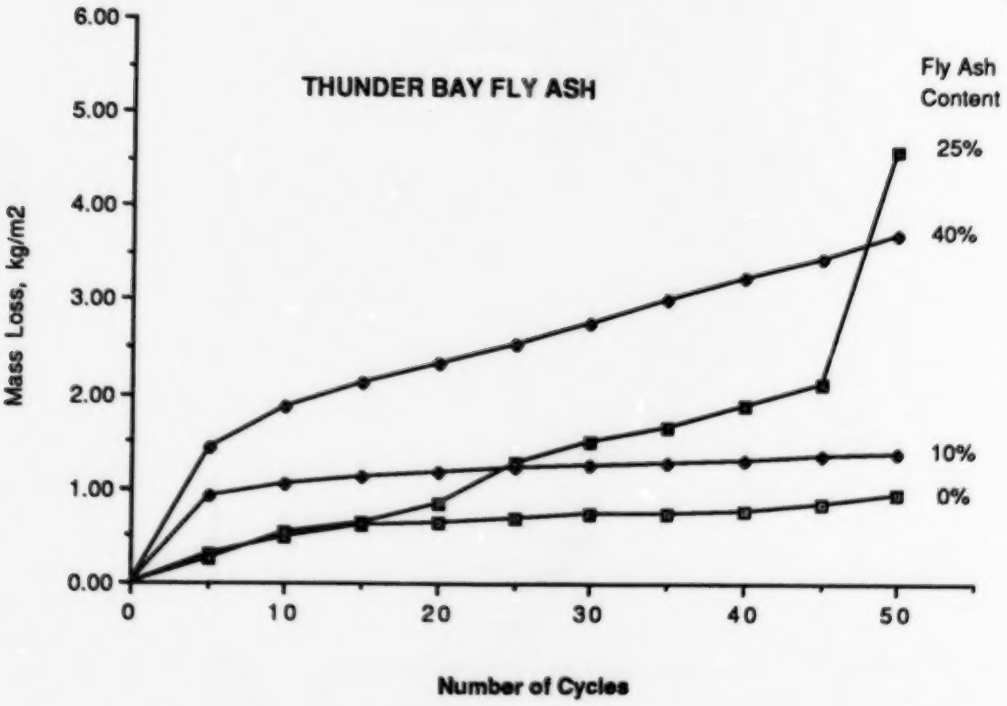


FIGURE 9-1. SALT SCALING RESISTANCE 20 MPa CONCRETE, CEMENT A

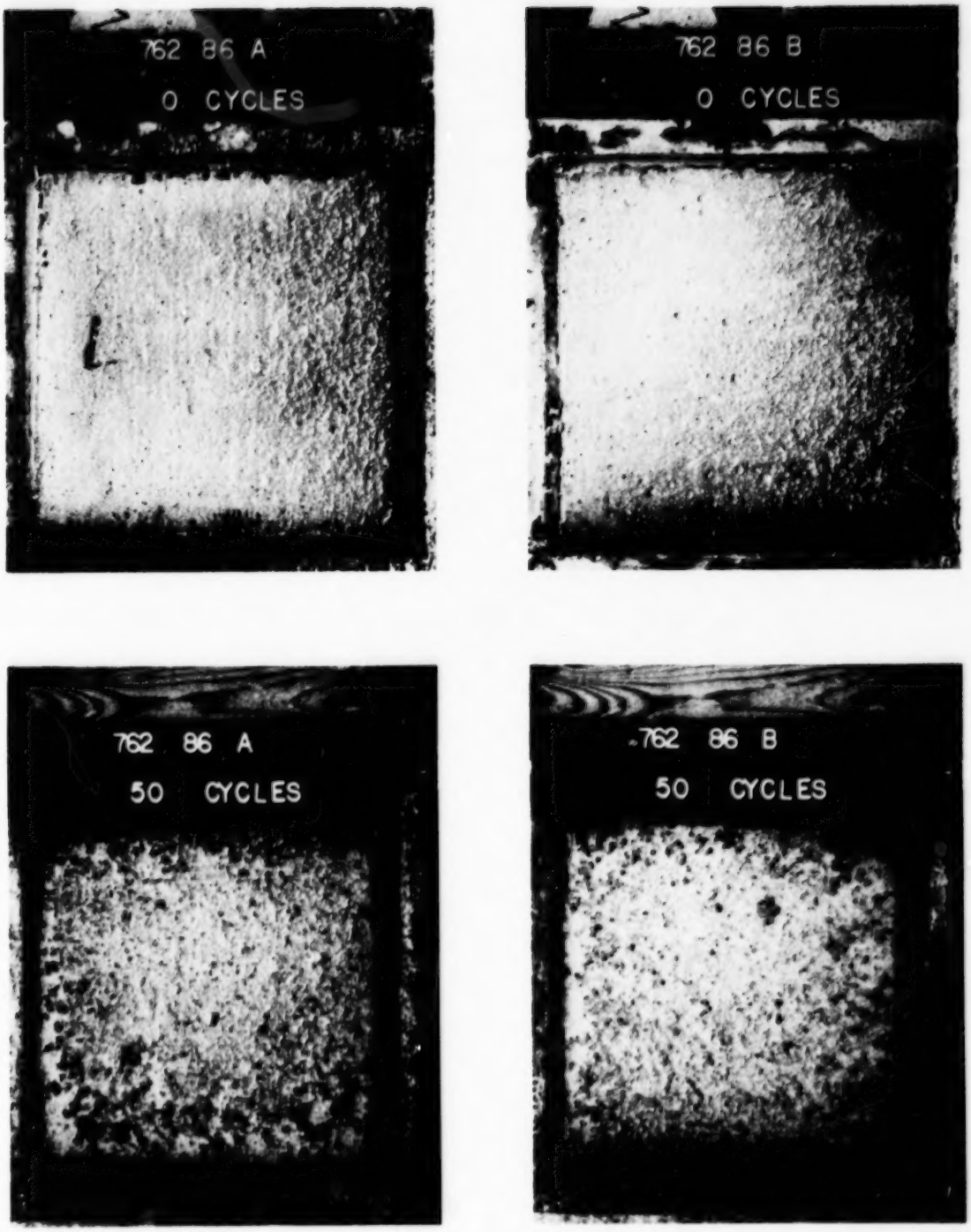


Figure 9-2 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Test.

20 MPa Concrete, Cement A, Control

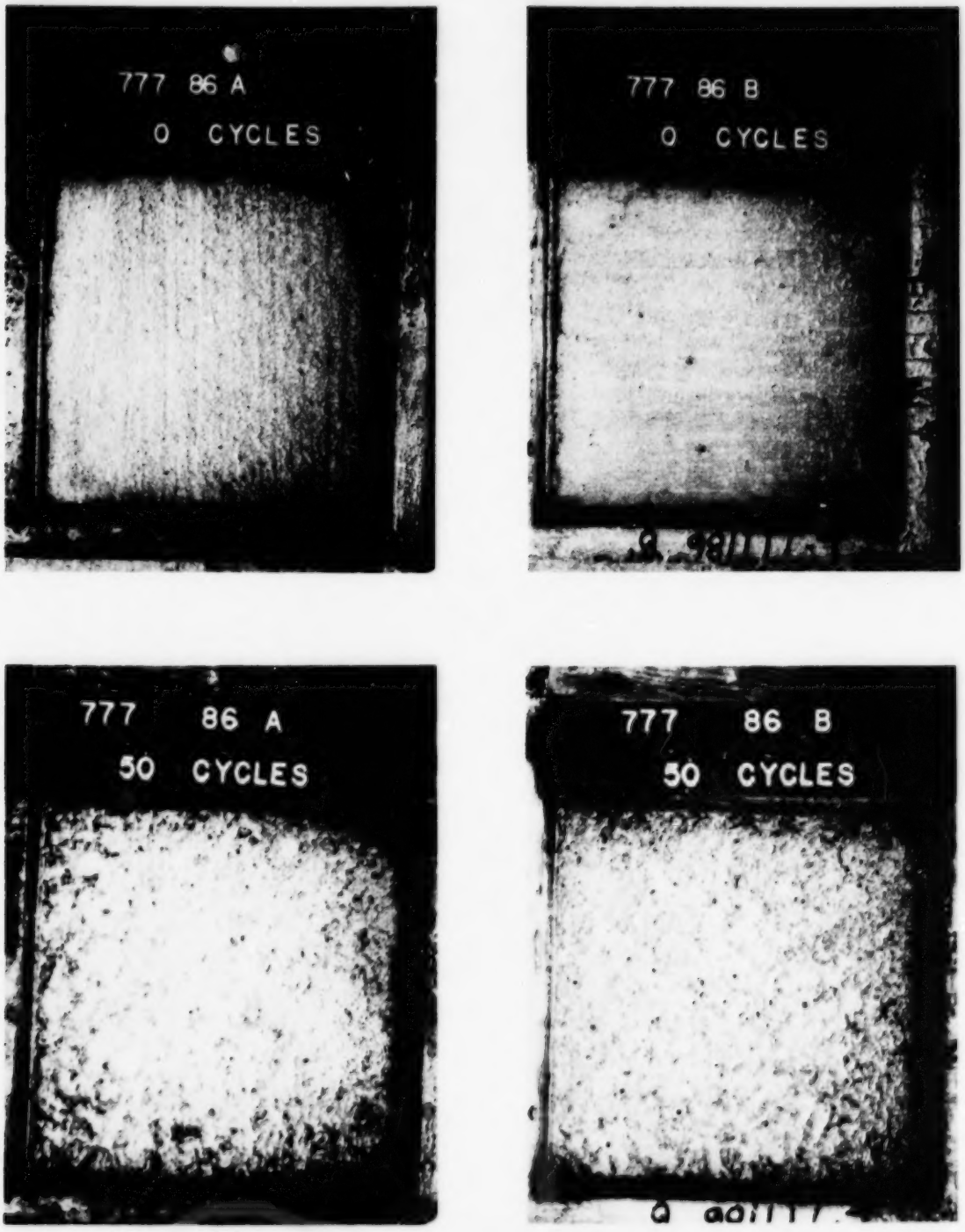


Figure 9-3 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

20 MPa Concrete, Cement A, St. Clair Fly Ash -10%

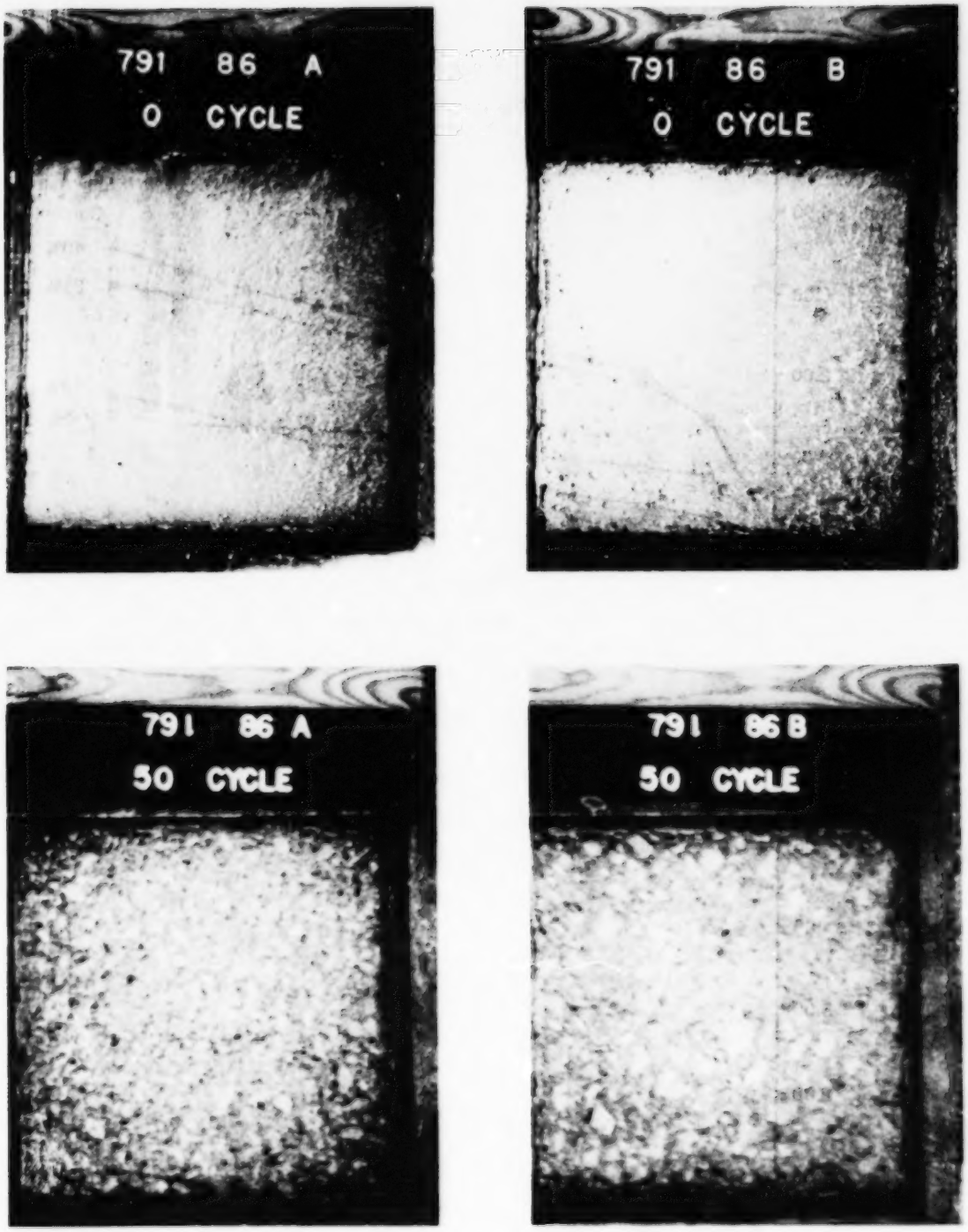
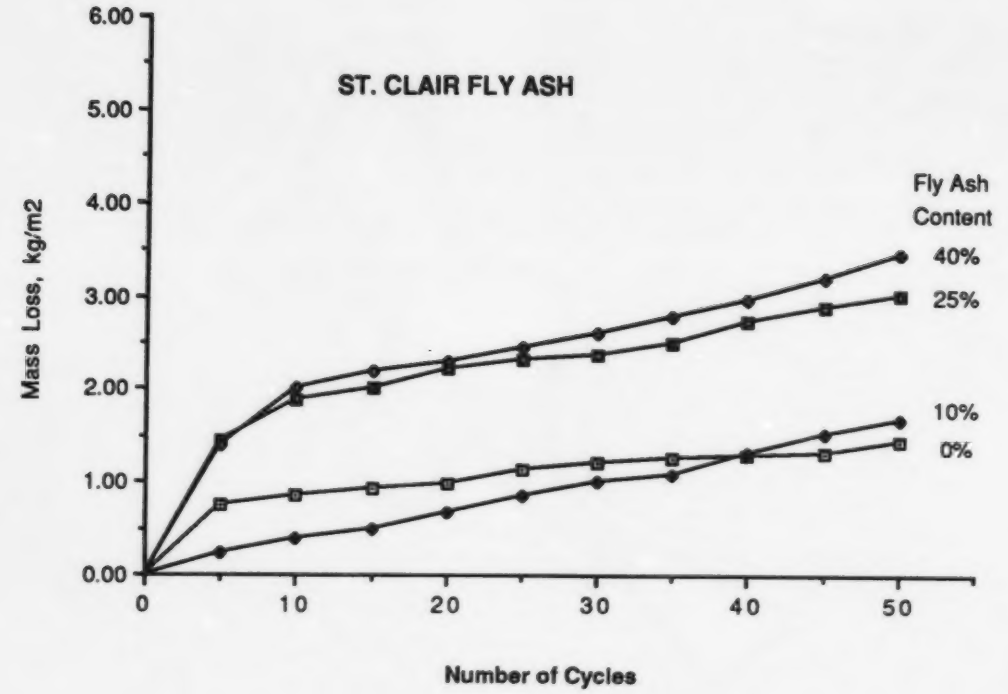


Figure 9-4 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

20 MPa Concrete, Cement A, Thunder Bay Fly Ash -10%



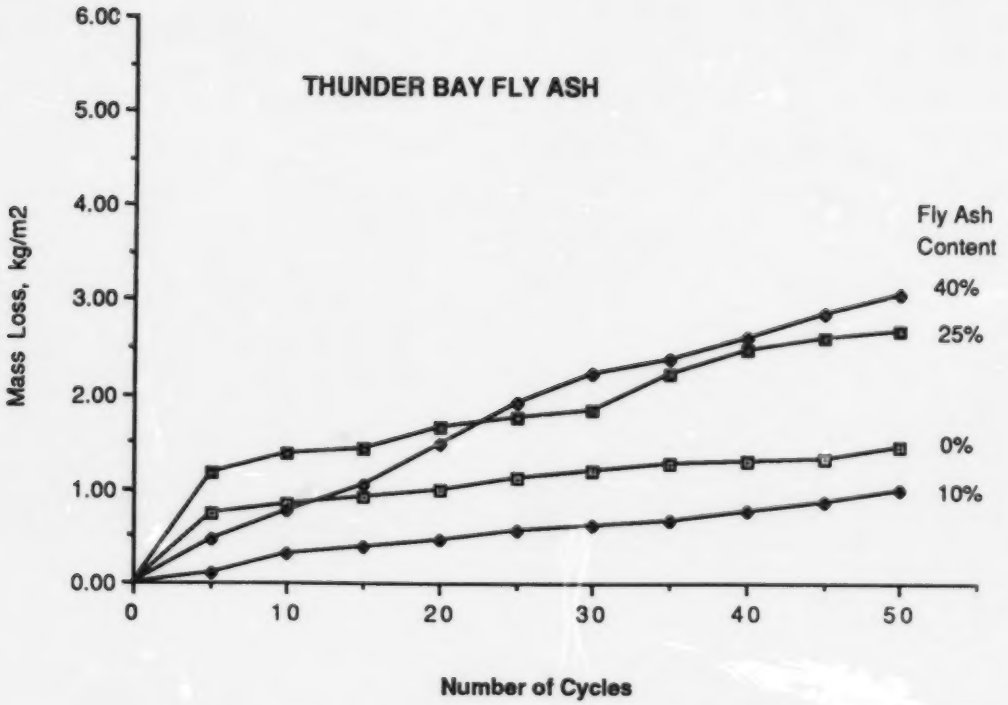


FIGURE 10-1. SALT SCALING RESISTANCE 20 MPa CONCRETE, CEMENT B

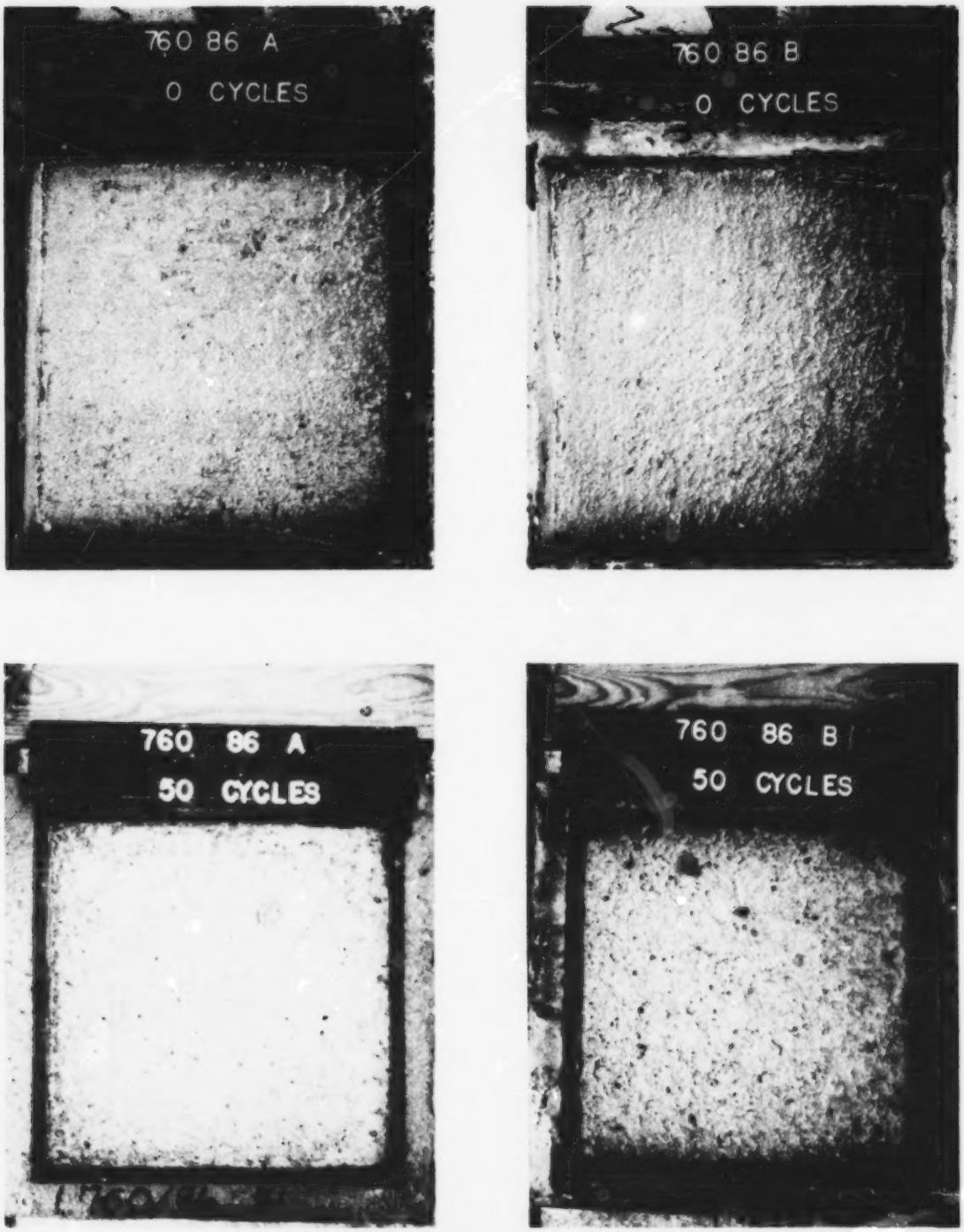


Figure 10-2 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

20 MPa Concrete, Cement B, Control

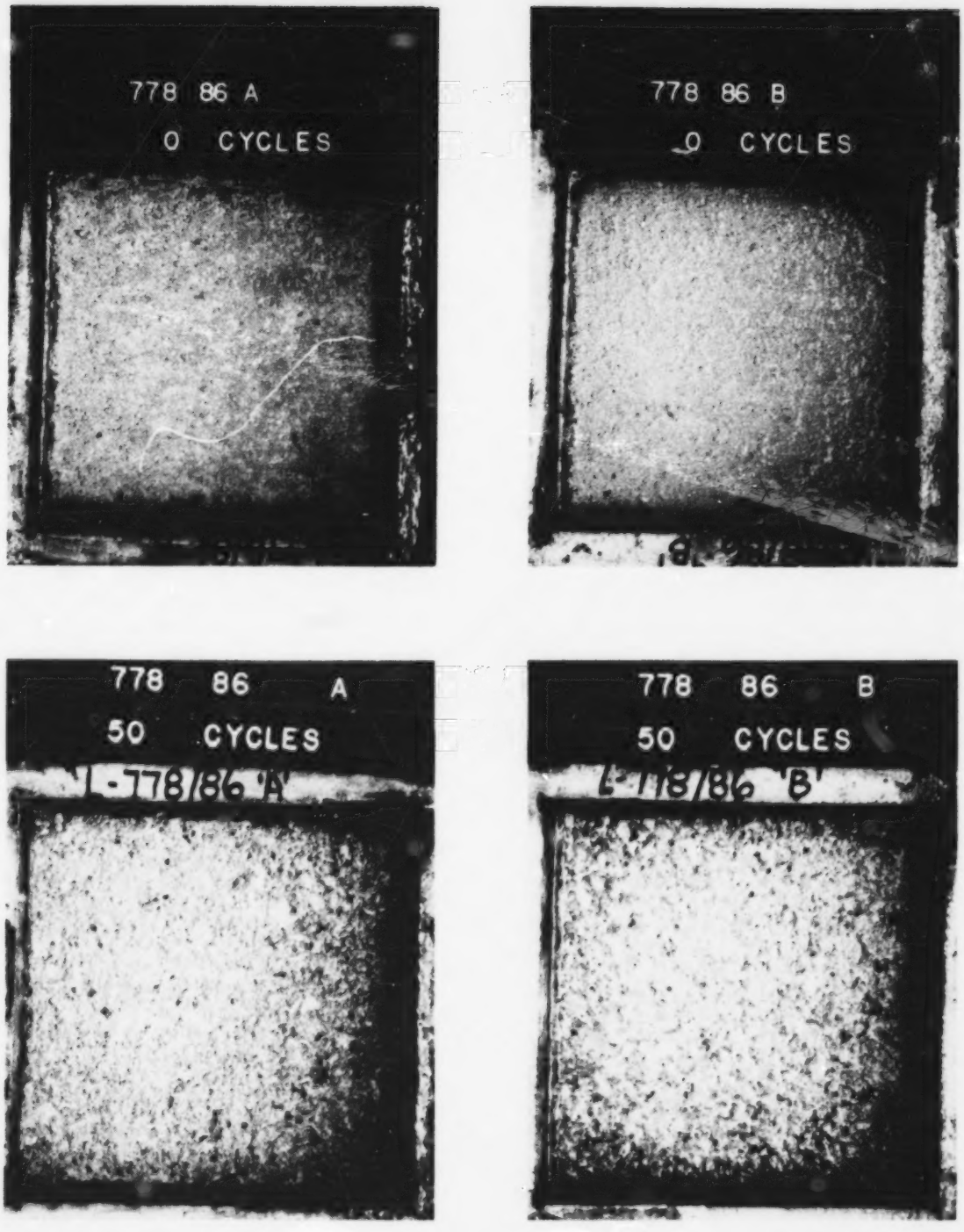


Figure 10-3 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

20 MPa Concrete, Cement B, St. Clair Fly Ash -10%

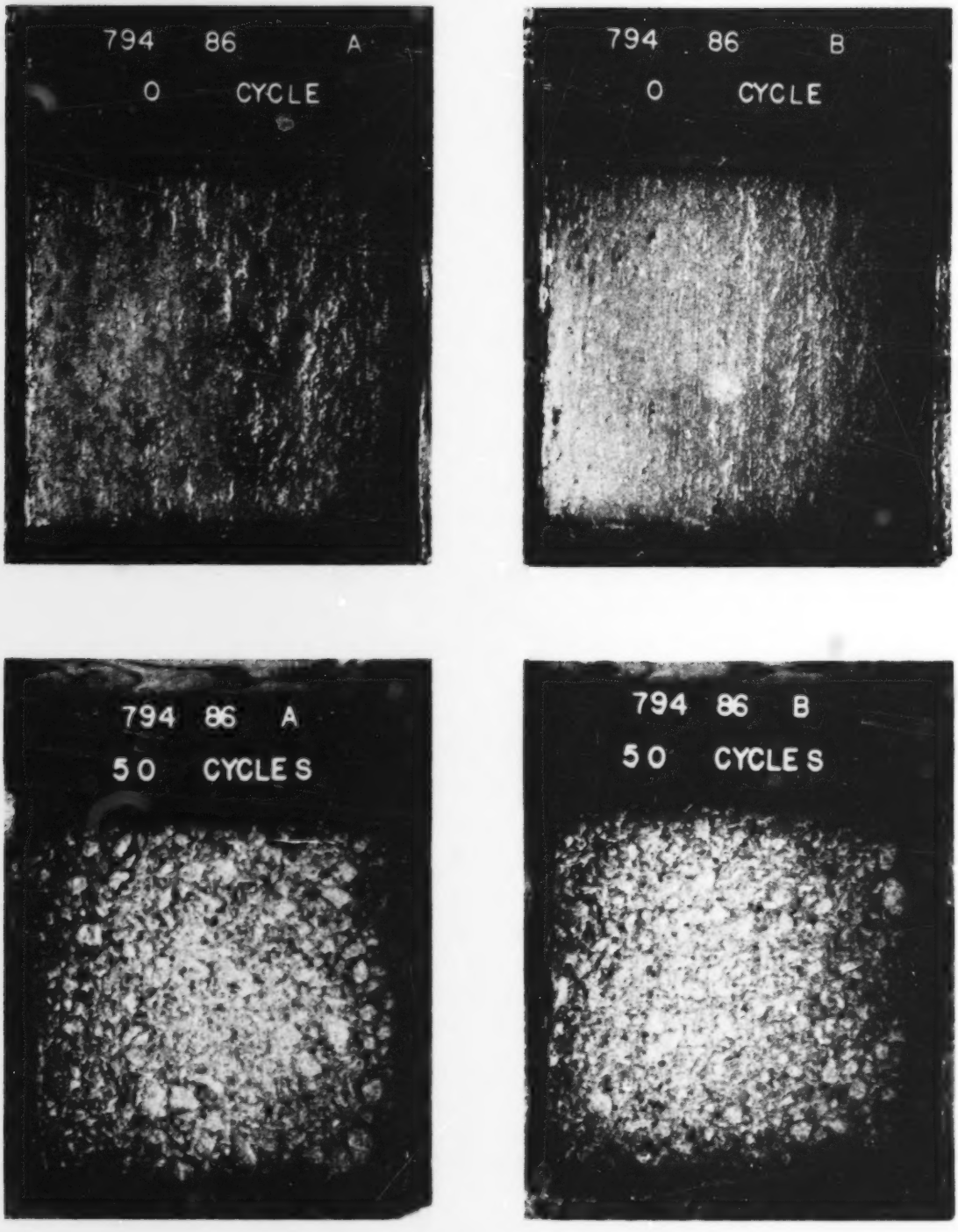


Figure 10-4 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

20 MPa Concrete, Cement B, St. Clair Fly Ash -25%

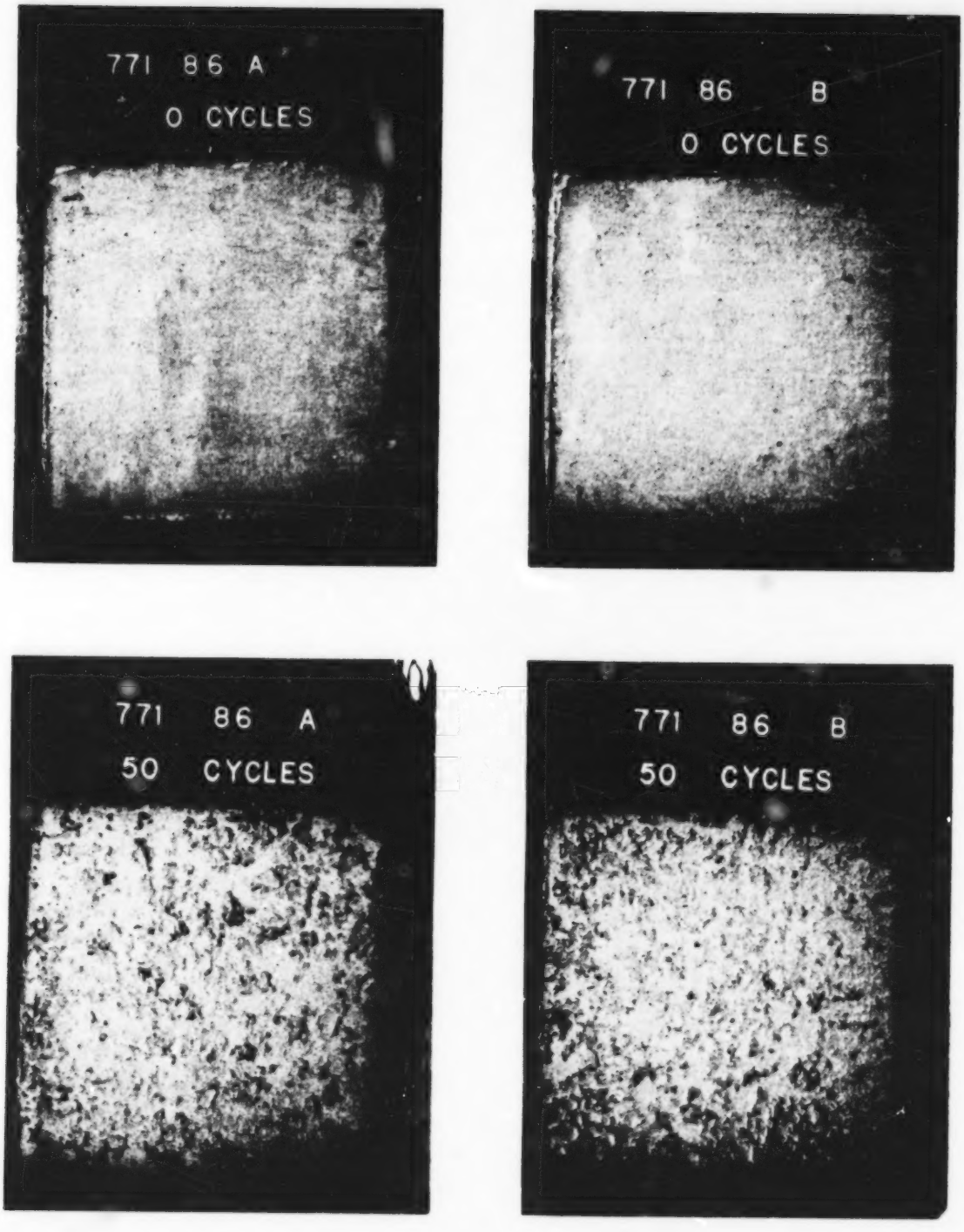
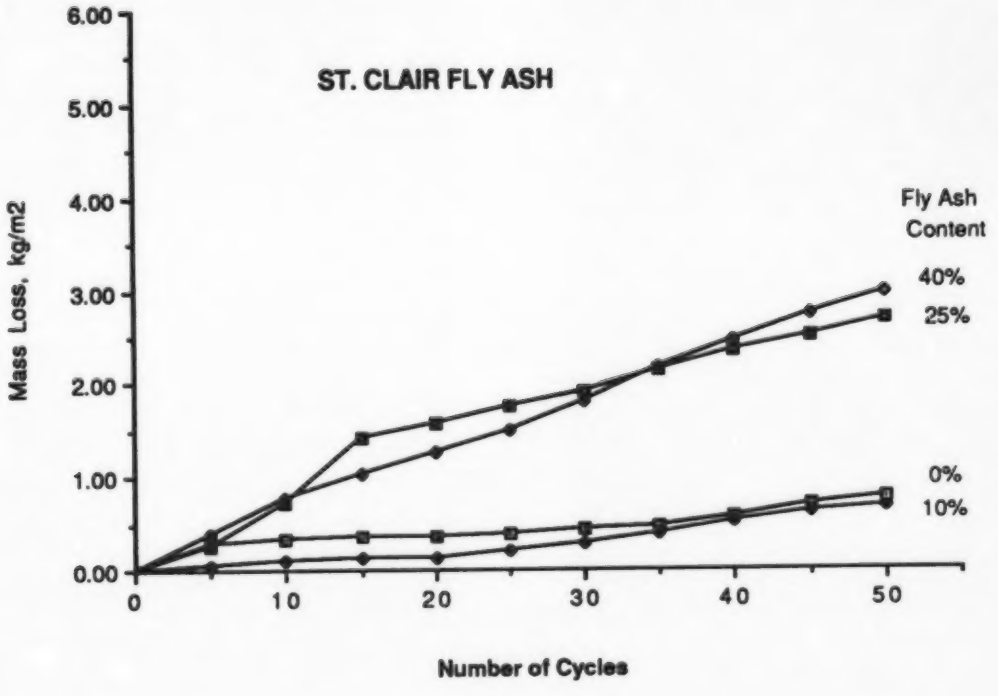


Figure 10-5 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

20 MPa Concrete, Cement B, Thunder Bay Fly Ash -10%



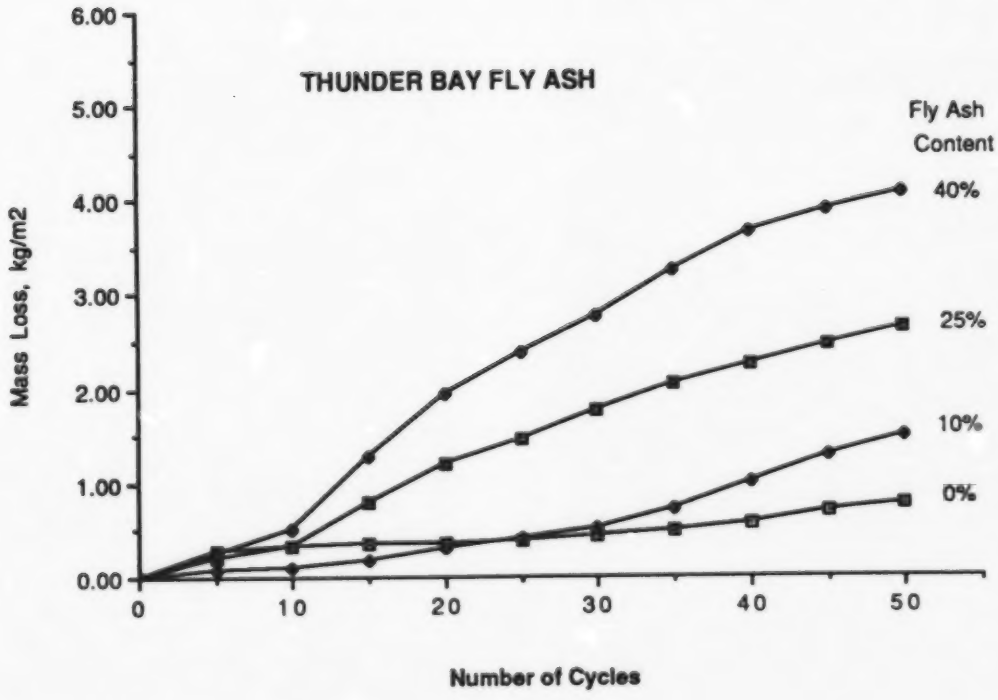


FIGURE 11-1. SALT SCALING RESISTANCE 35 MPa CONCRETE, CEMENT A

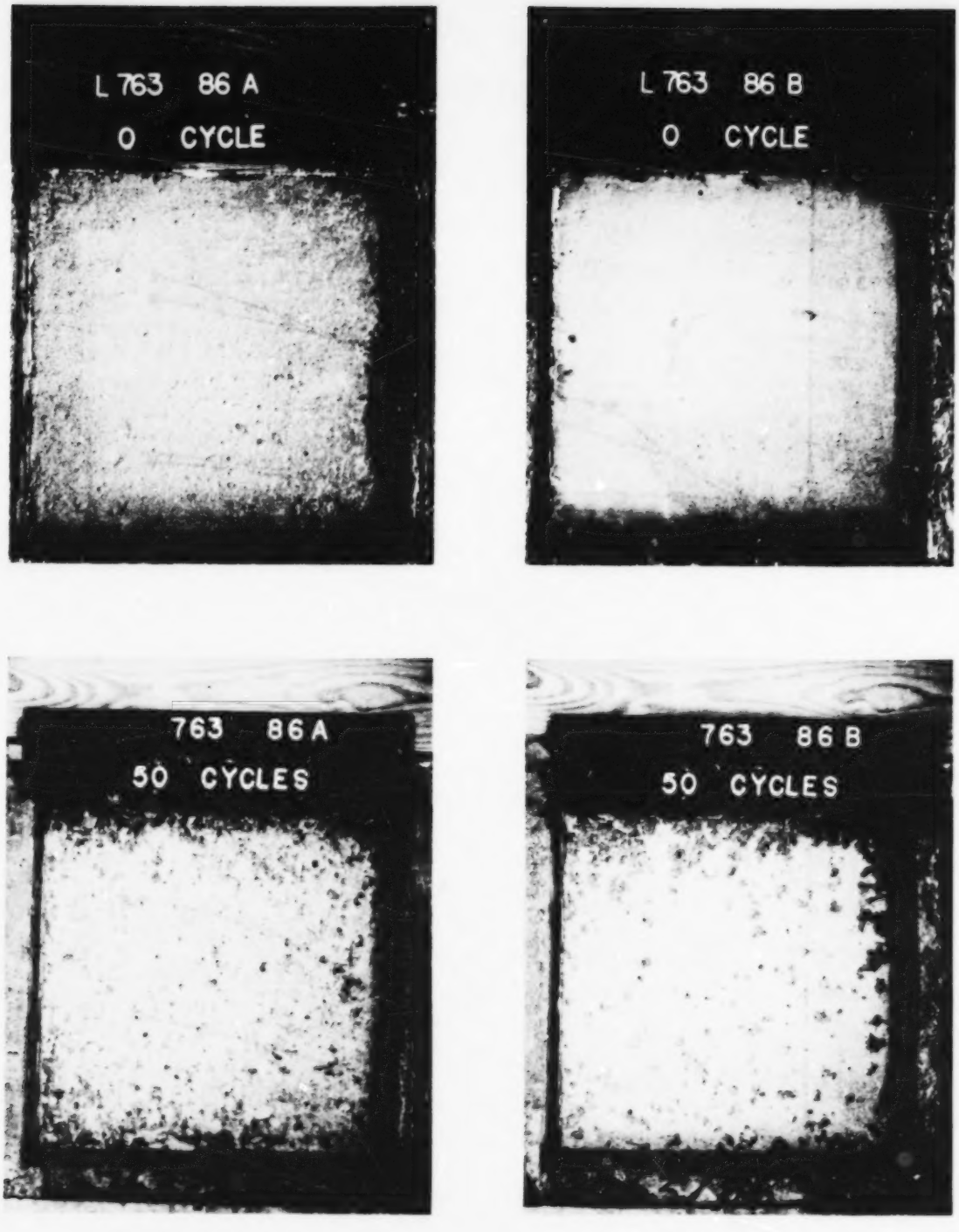


Figure 11-2 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

35 MPa Concrete, Cement A, Control

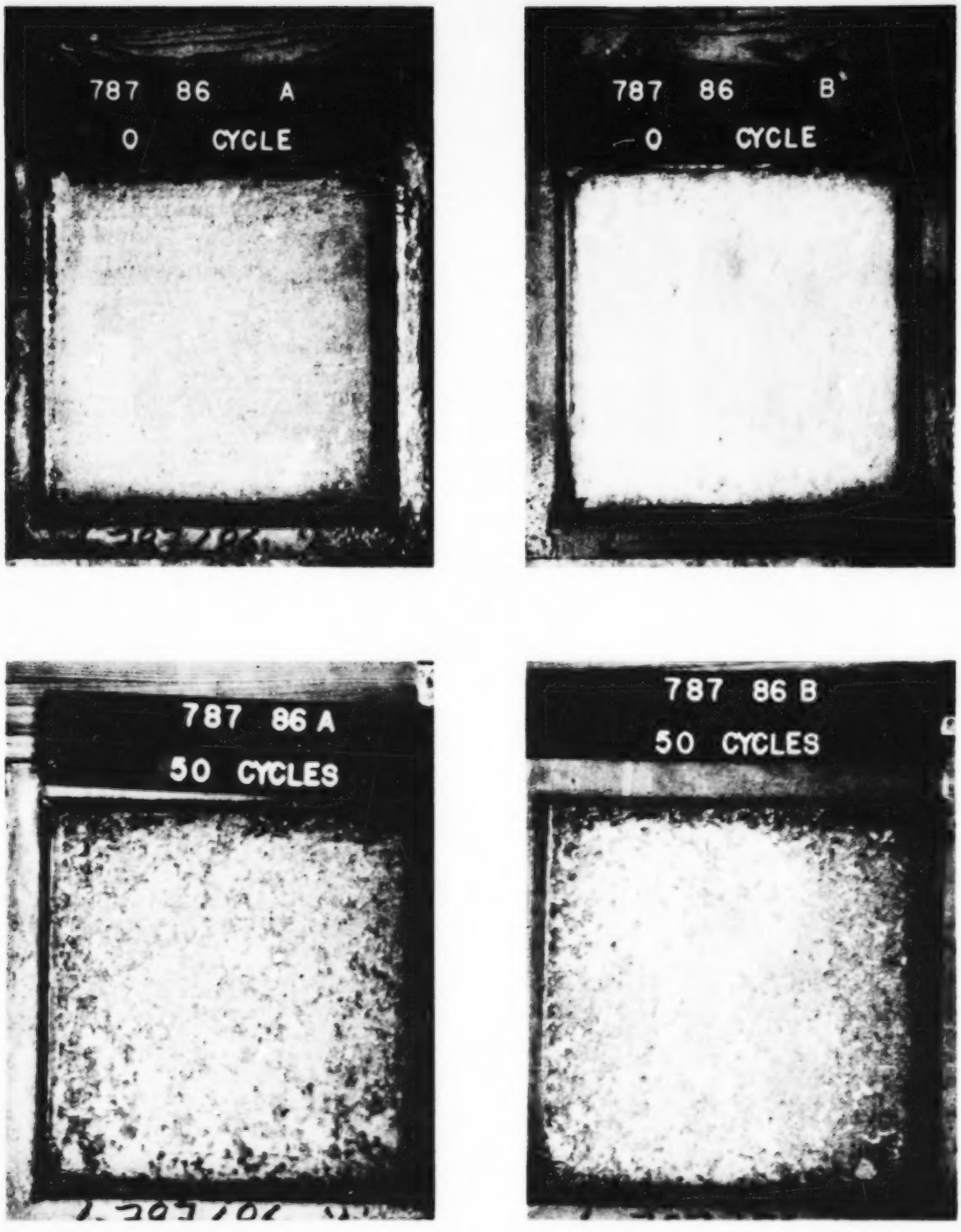


Figure 11-3 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

35 MPa Concrete, Cement A, St. Clair Fly Ash -10%

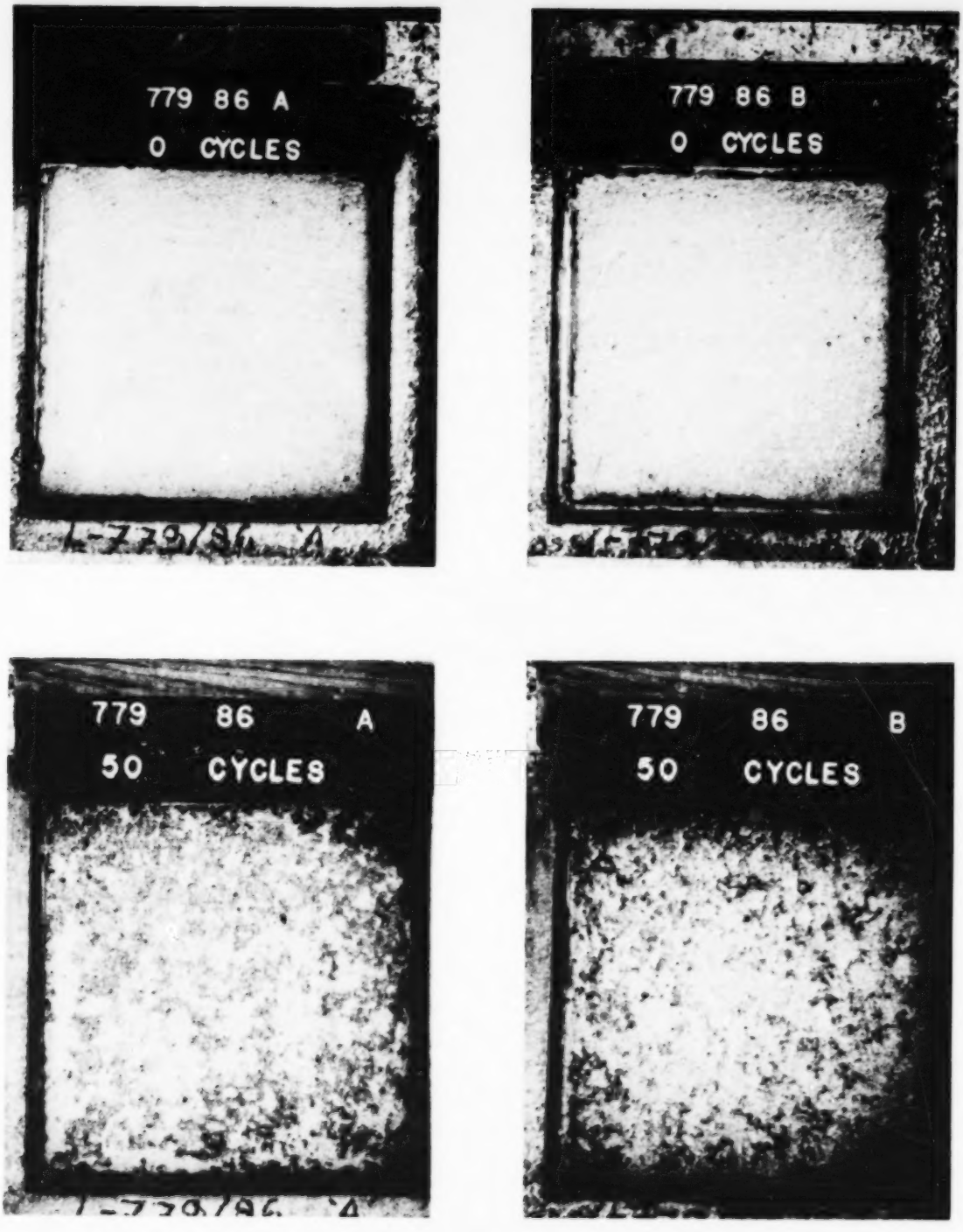
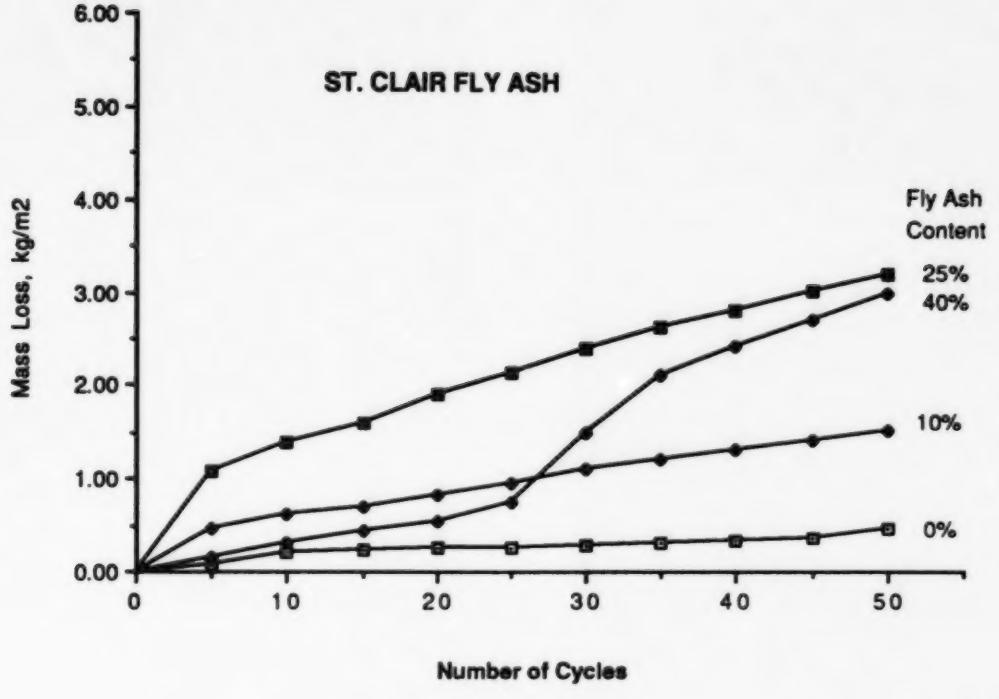


Figure 11-4 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

35 MPa Concrete, Cement A, Thunder Bay Fly Ash -10%



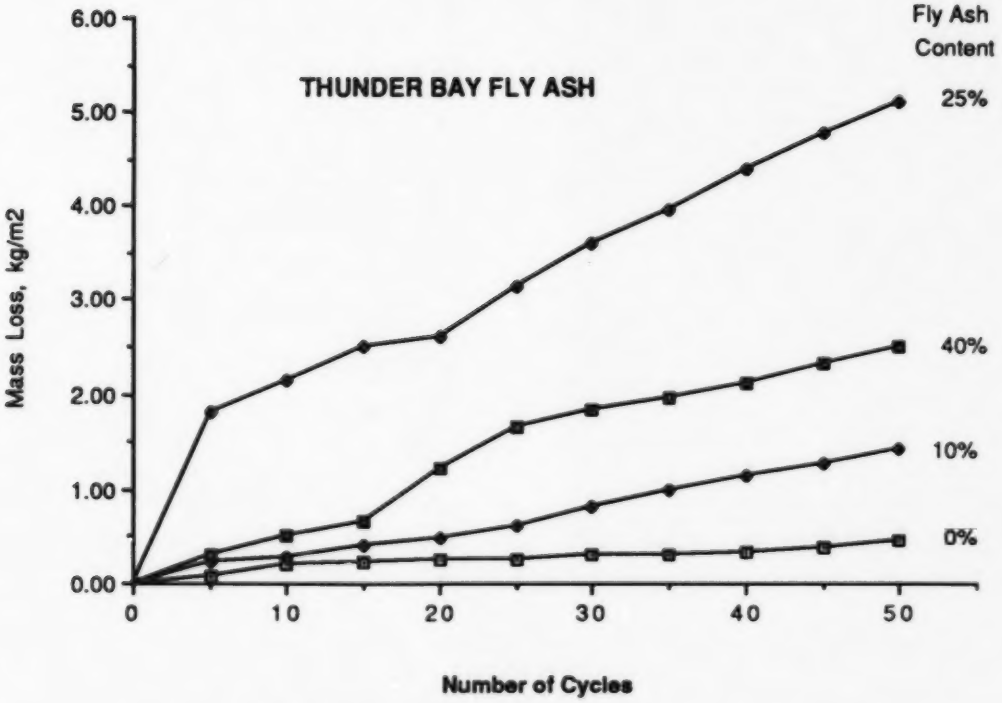


FIGURE 12-1. SALT SCALING RESISTANCE 35 MPa CONCRETE, CEMENT B

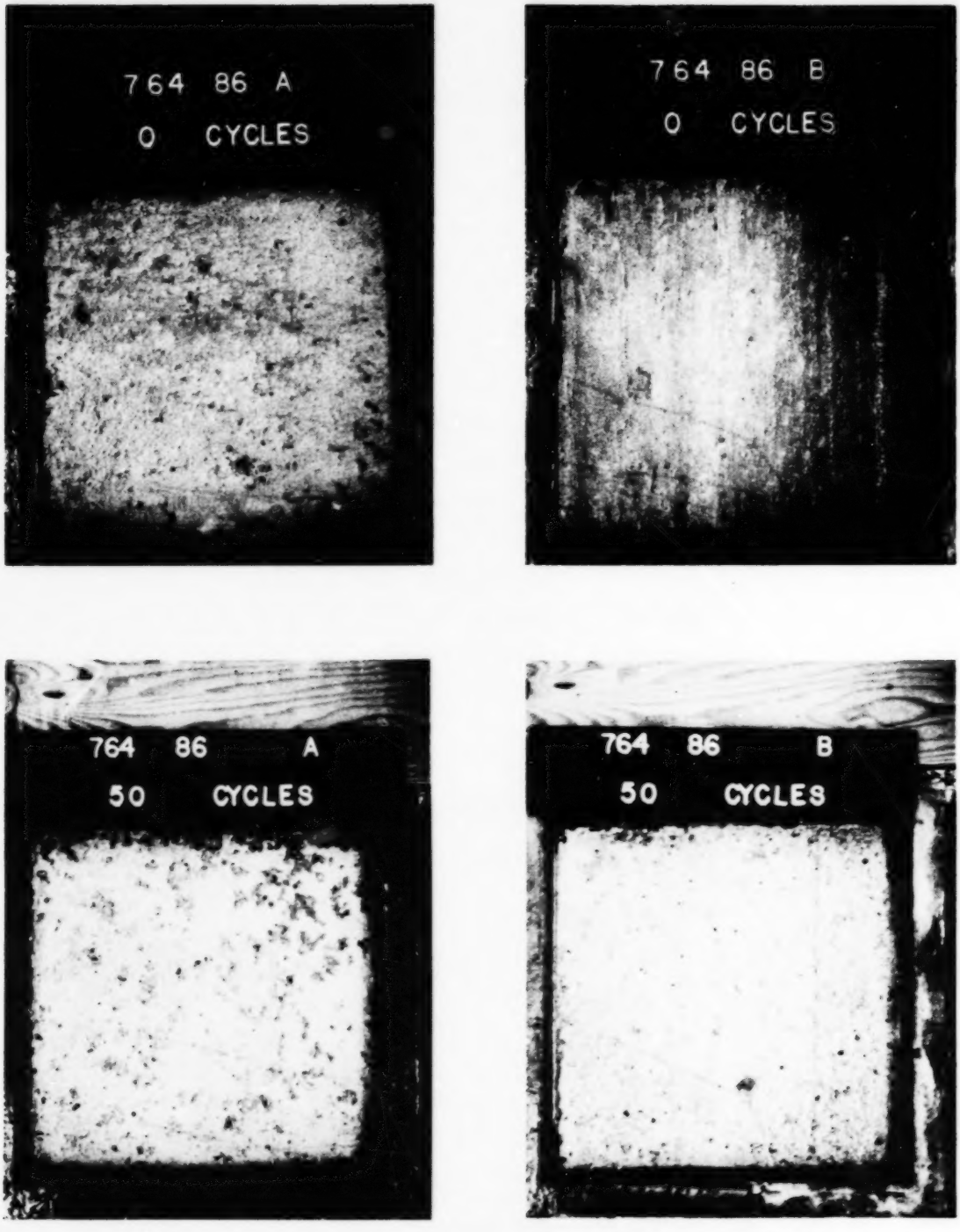


Figure 12-2 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

35 MPa Concrete, Cement B, Control

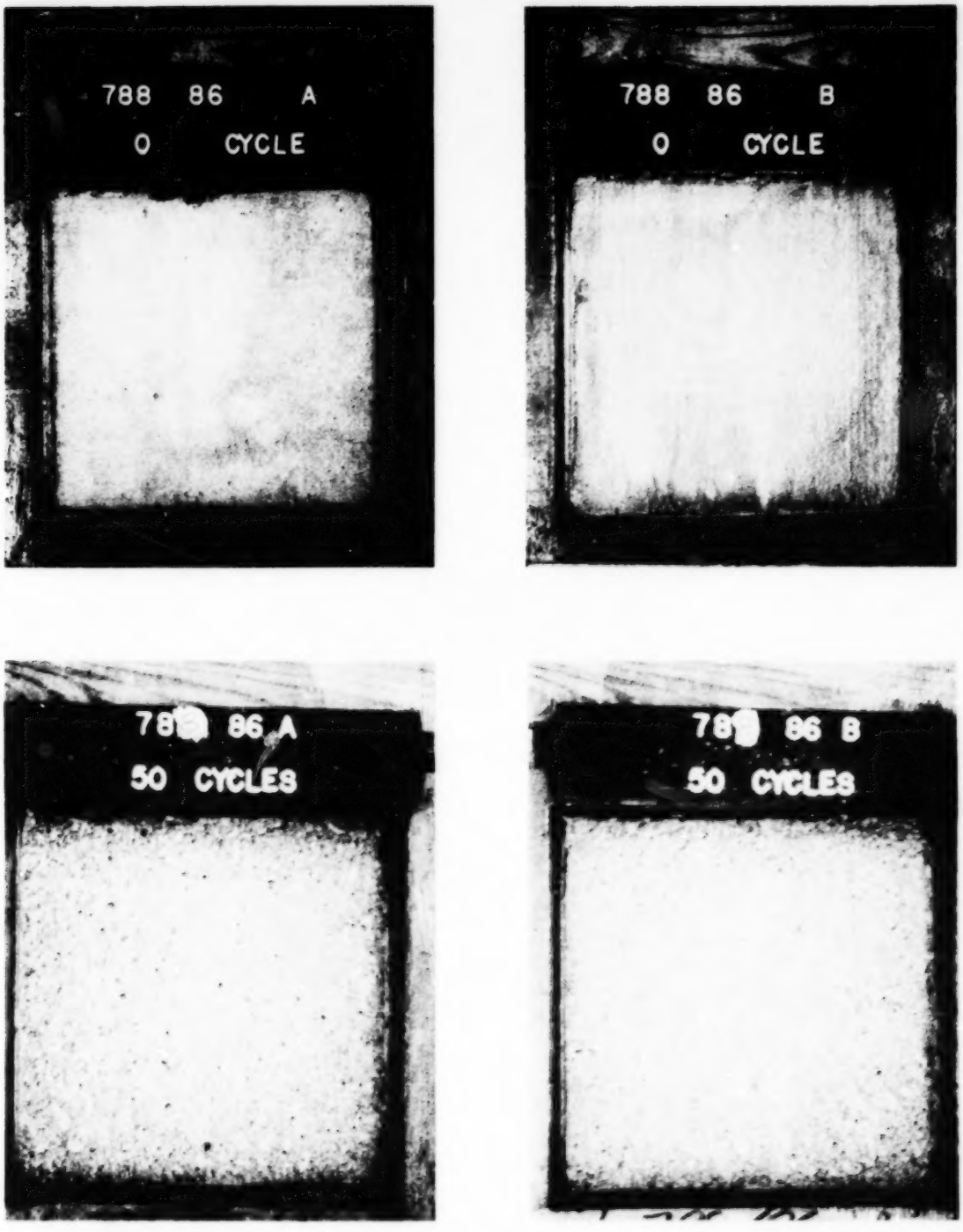


Figure 12-3 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

35 MPa Concrete, Cement B, St. Clair Fly Ash -10%

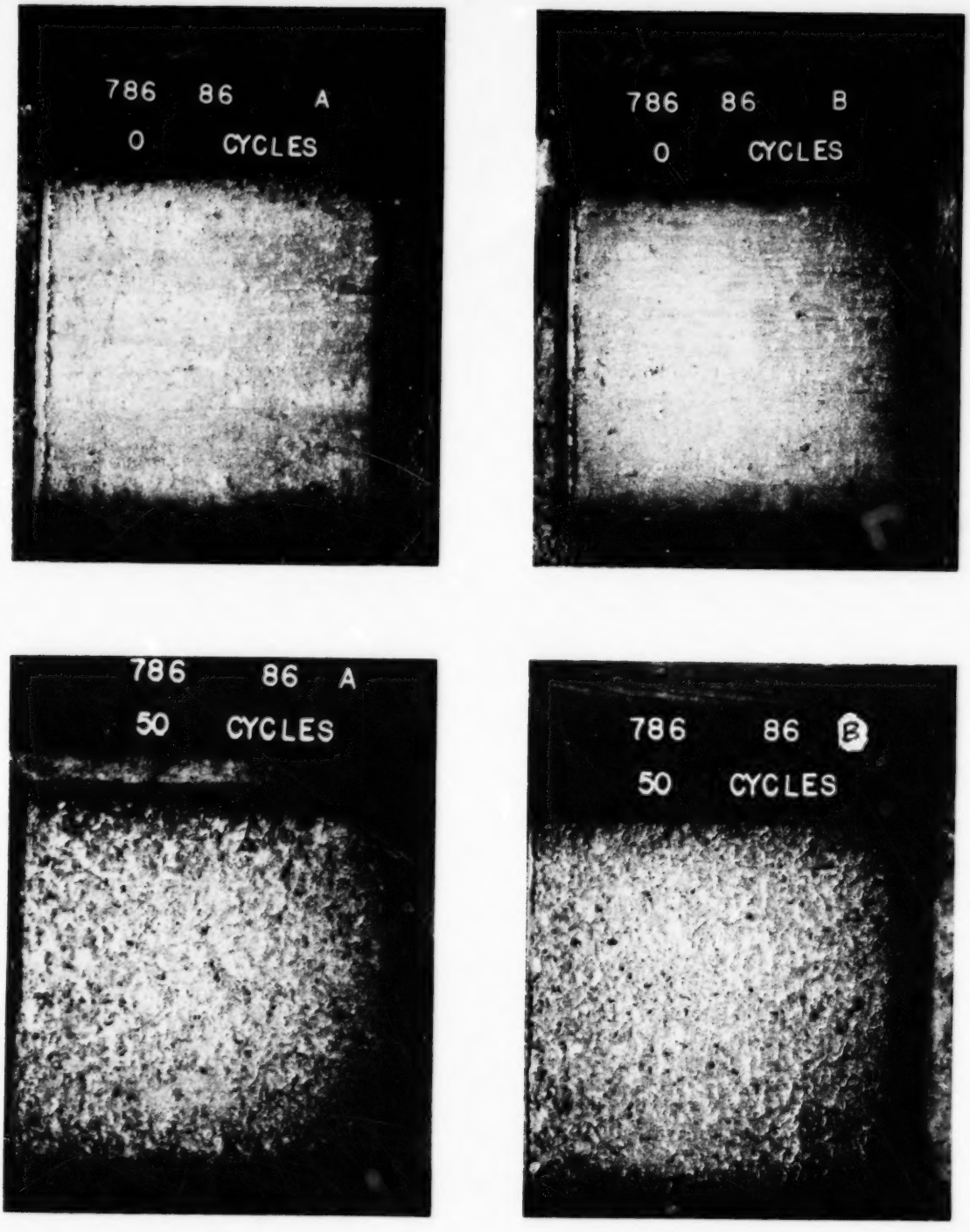


Figure 12-4 Appearance of Salt Scaling Slabs Before Starting and After Completion of the Tests.

35 MPa Concrete, Cement B, Thunder Bay Fly Ash -10%

Figure 13 Casting of test specimens at the job site

Figure 14 Curing of the barrier wall

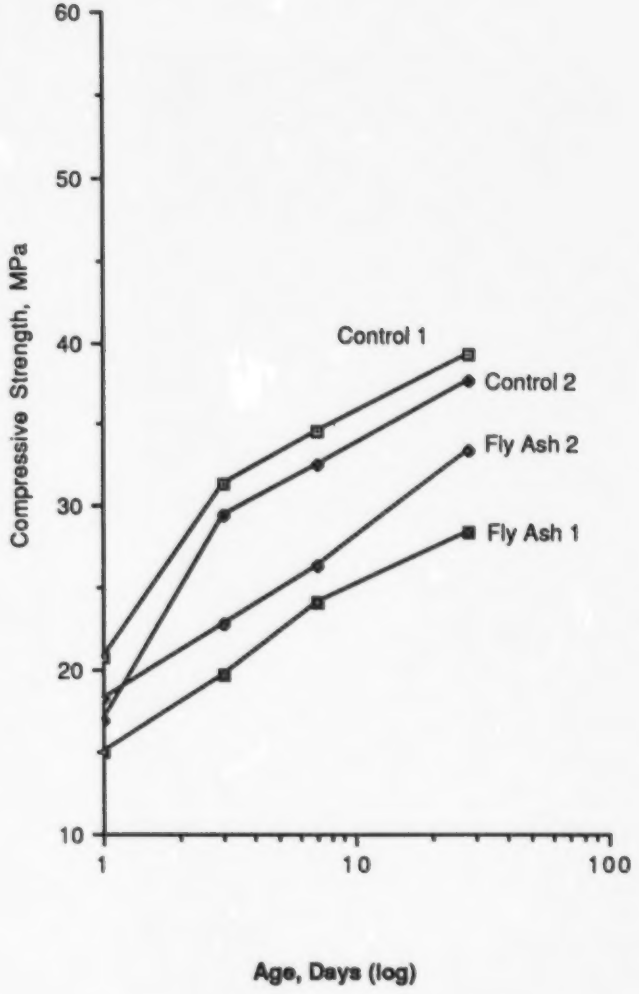


FIGURE 15. COMPRESSIVE STRENGTH TEST RESULTS FIELD PROJECT

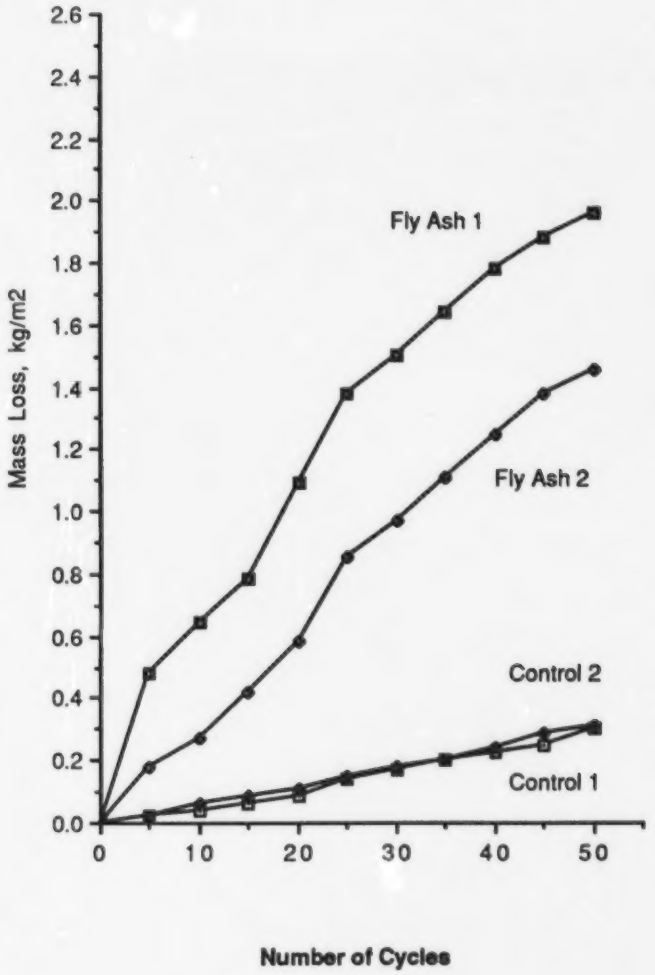


FIGURE 16-1. SALT SCALING RESISTANCE FIELD PROJECT

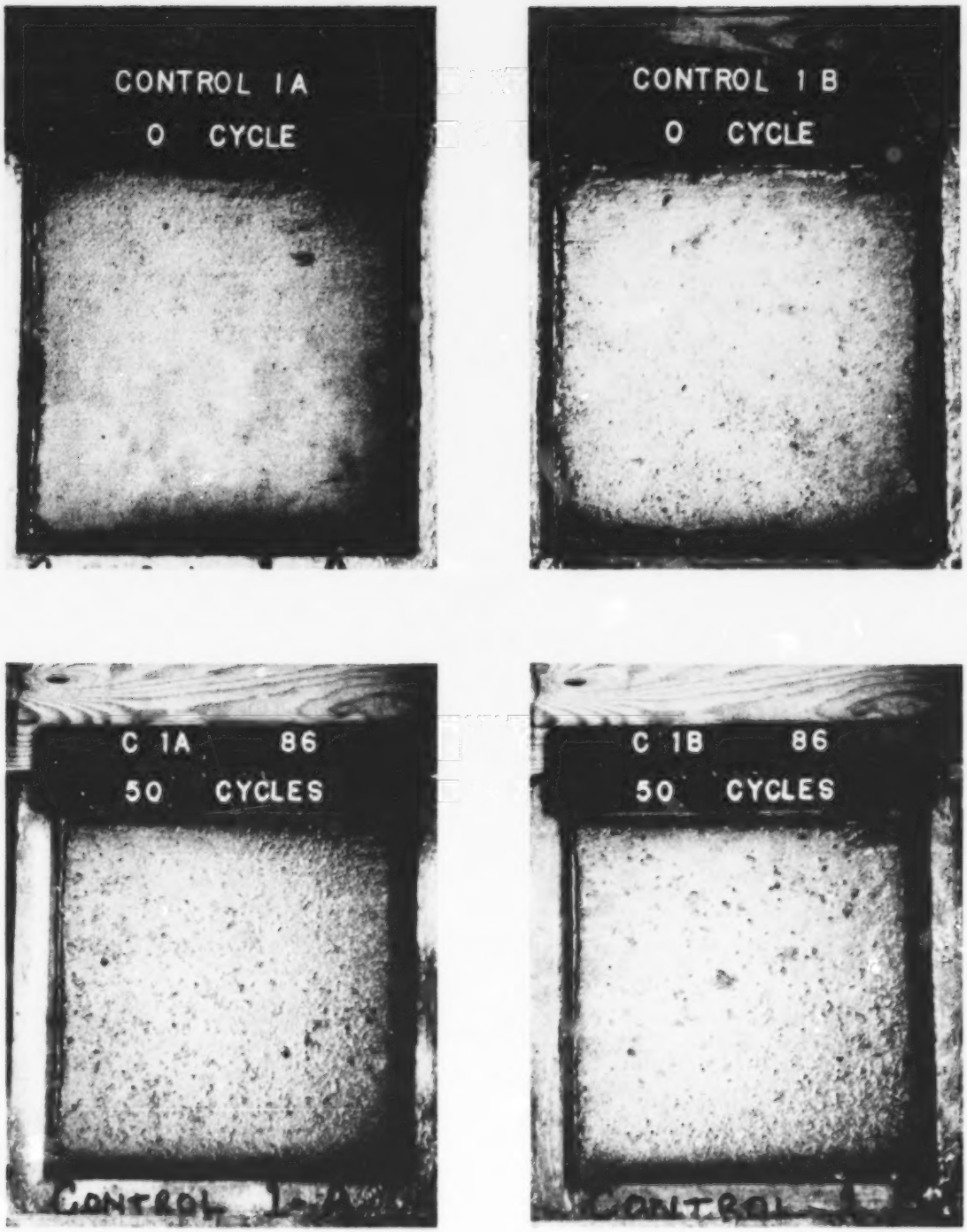


Figure 16-2 Appearance of Salt Scaling Slabs at the Start and Completion of the Test.

Field Project, Control 1

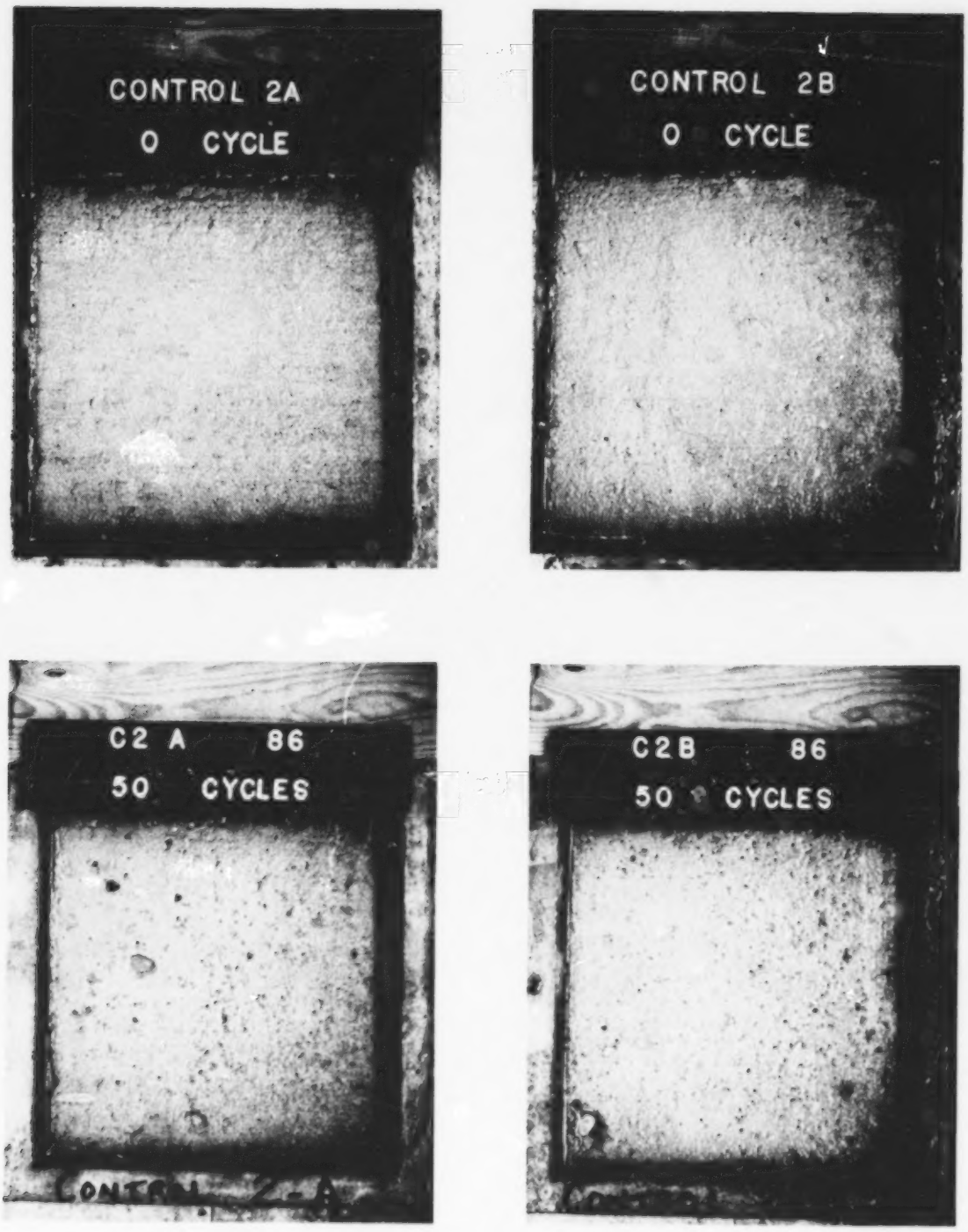


Figure 16-3 Appearance of Salt Scaling Slabs at the Start and Completion of the Test.

Field Project, Control 2

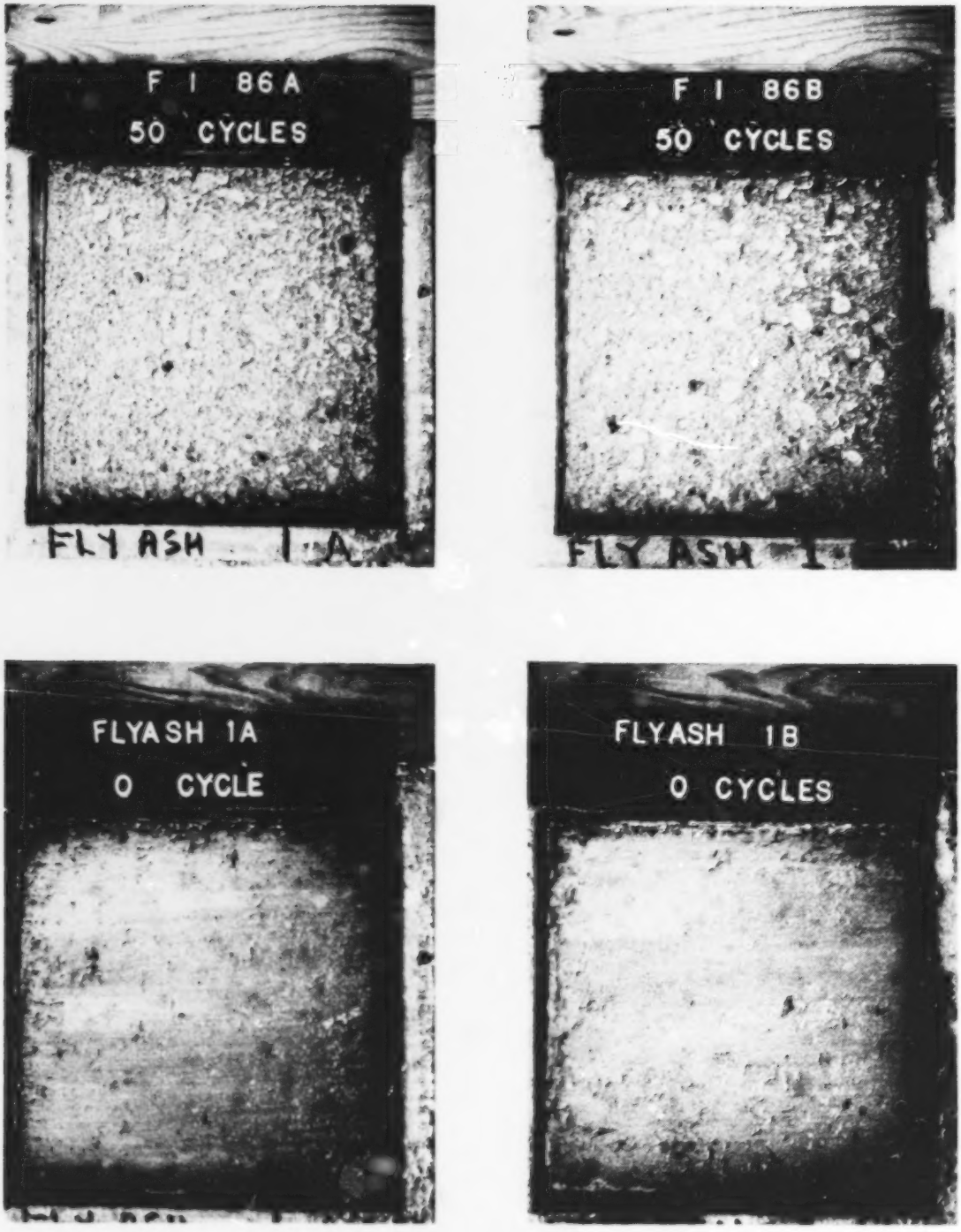


Figure 16-4 Appearance of Salt Scaling Slabs at the Start and Completion of the Test.

Field Project, Fly Ash 1

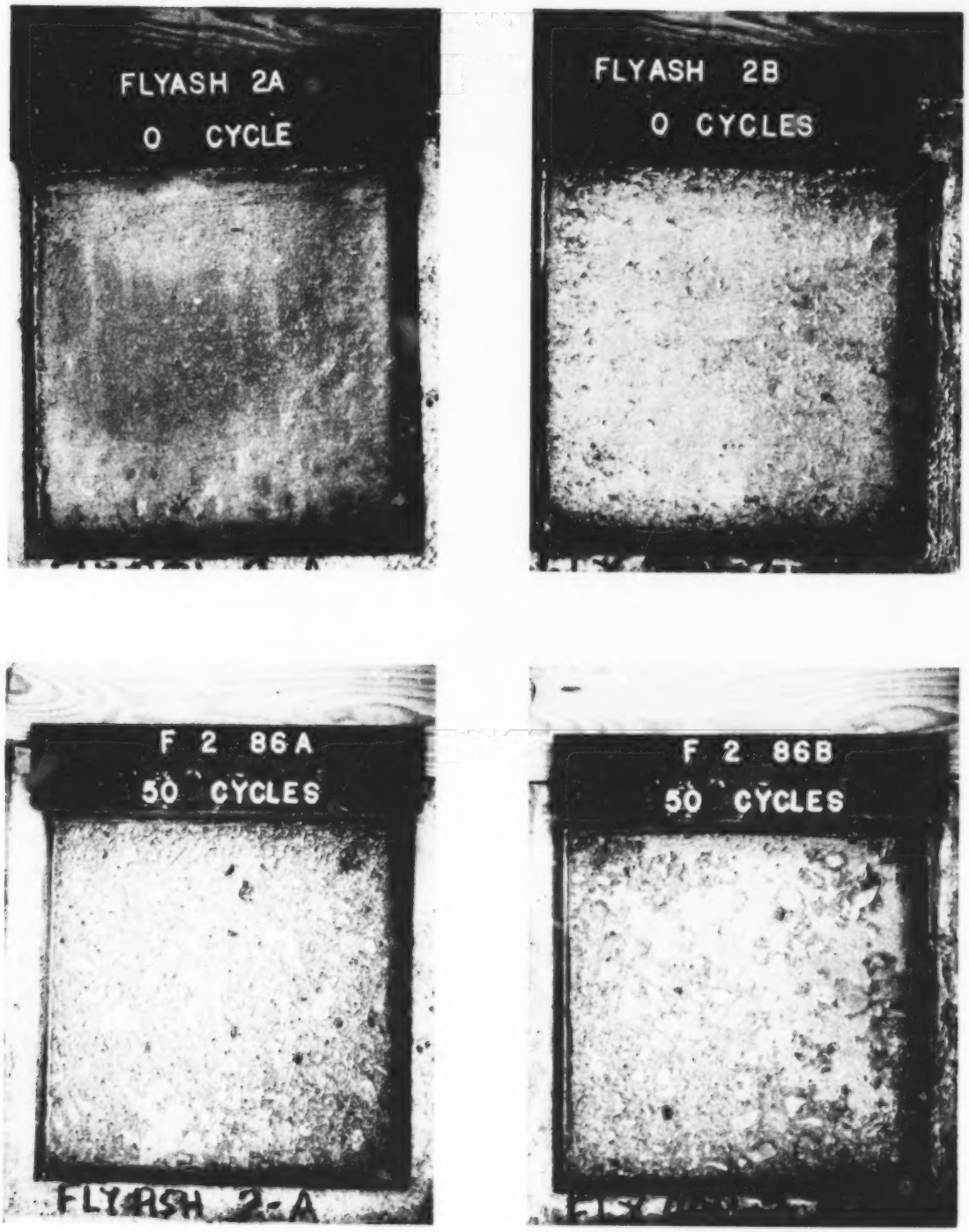


Figure 16-5 Appearance of Salt Scaling Slabs at the Start and Completion of the Test.

Field Project, Fly Ash 2

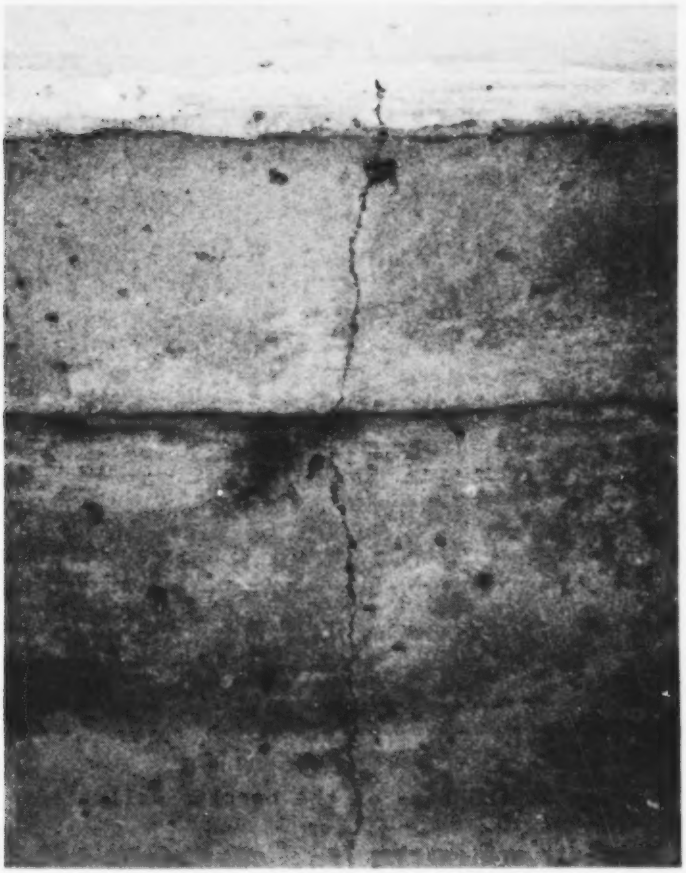


Figure 17 A vertical crack in mid-length of panel

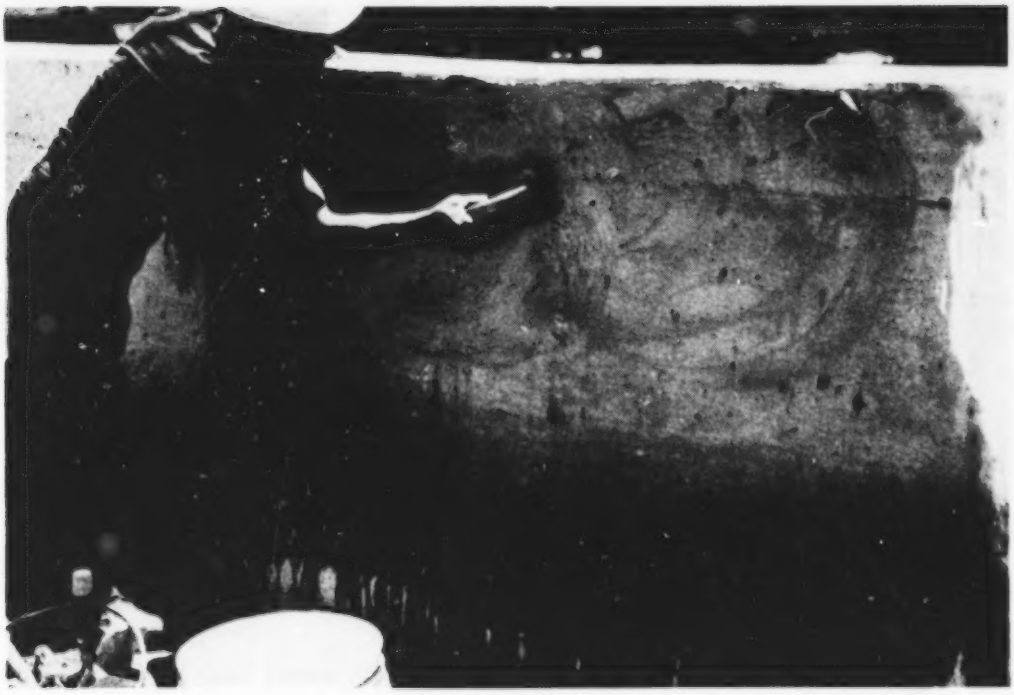


Figure 18 Rubbing sand-cement grout into the surface to fill bugholes

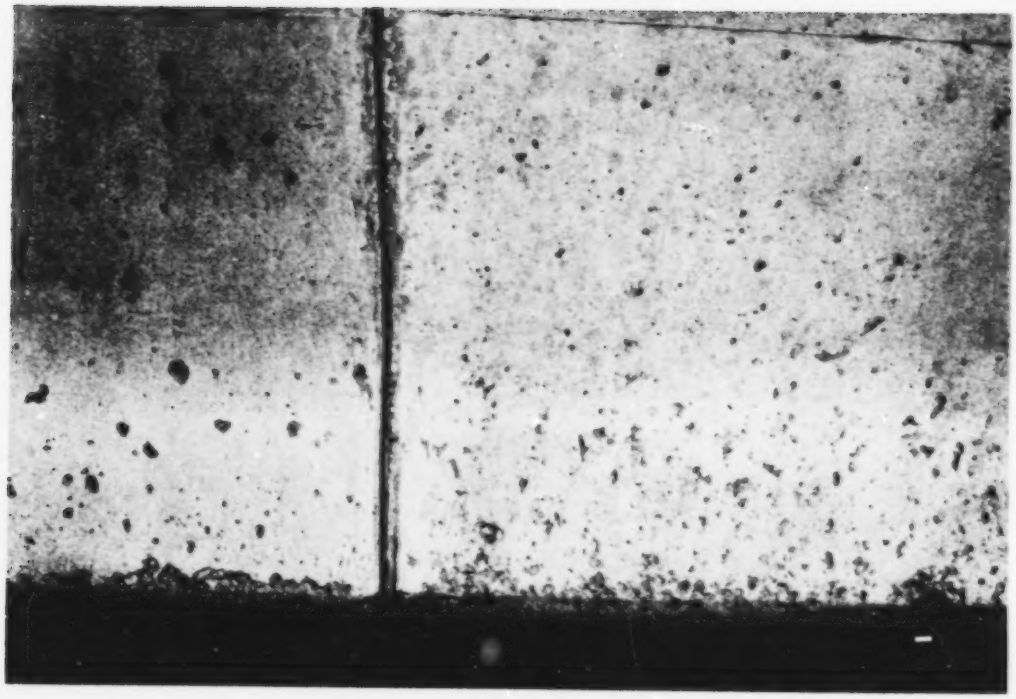


Figure 19 Scaling at the base of the barrier wall (left-control panel; right-fly ash panel)

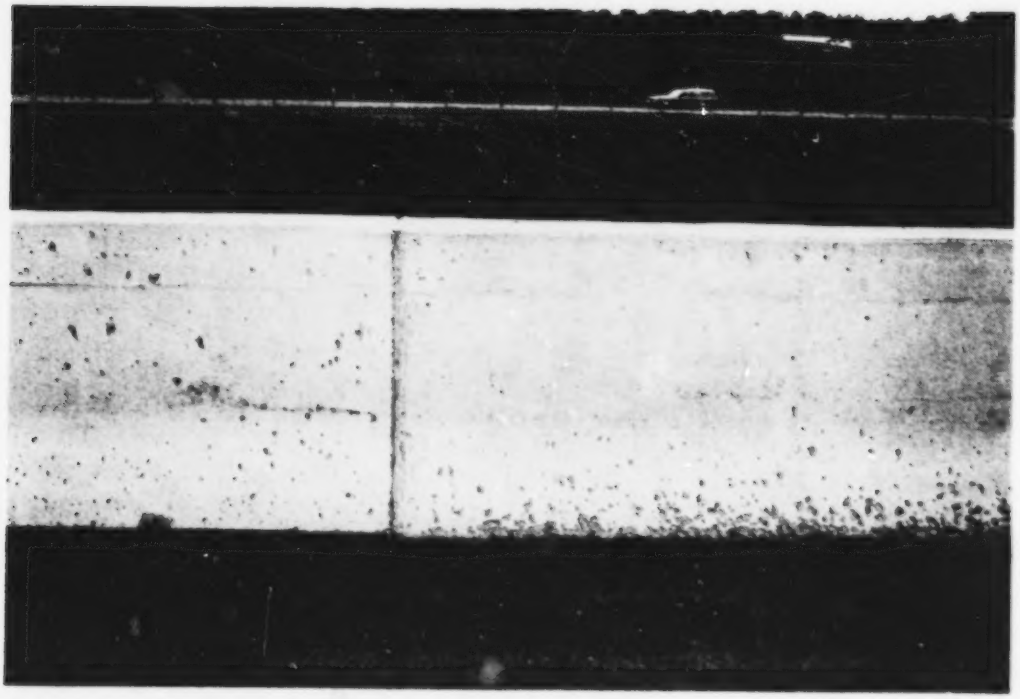


Figure 20 Scaling at the base of the fly ash panel (right of the joint)